February 11, 2021

# Sound Pressure, Sound Power and Uncertainty in Noise Measurements

Vibro-Acoustics Consortium Web Meeting

University of Kentucky

# Overview

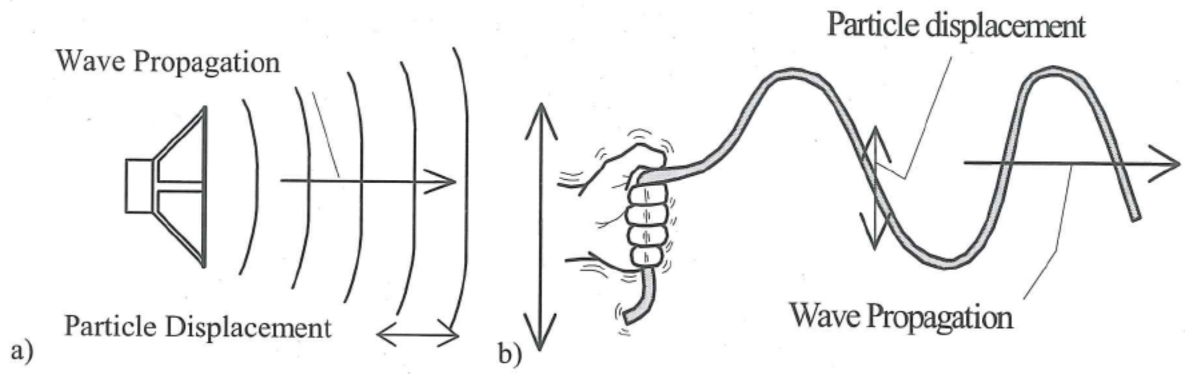
- Sound Pressure and Sound Power
- Measuring Sound Power
- Variability of Sound Pressure Measurements
- Variability of Sound Power Measurements

# Sound and Vibration Fields

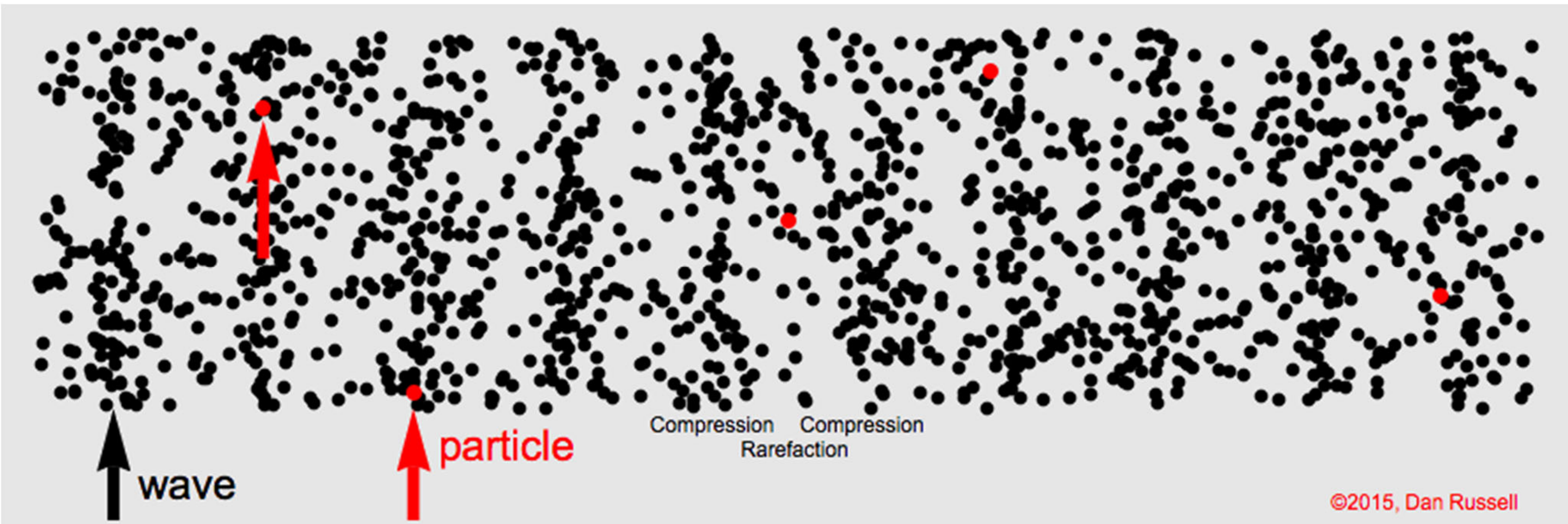
Sound and vibration waves are mechanical elastic waves, and thus the conditions for their existence are that the medium possess mass and elasticity (i.e., stiffness). If a mass particle is displaced from its equilibrium position, the elastic forces will seek to return it to its original position. The particle influences the surrounding particles and in this way, a disturbance (i.e., wave) propagates through the medium.

Wallin et al., 2011

Longitudinal                    Transverse



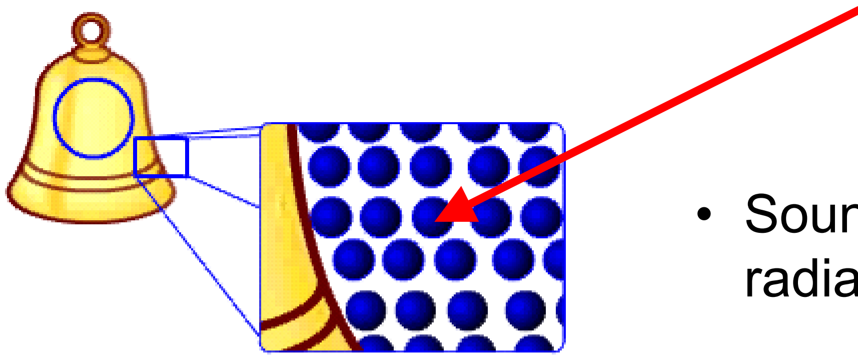
# Particle Motion




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

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

# Sound Intensity and Power



$$u, p$$

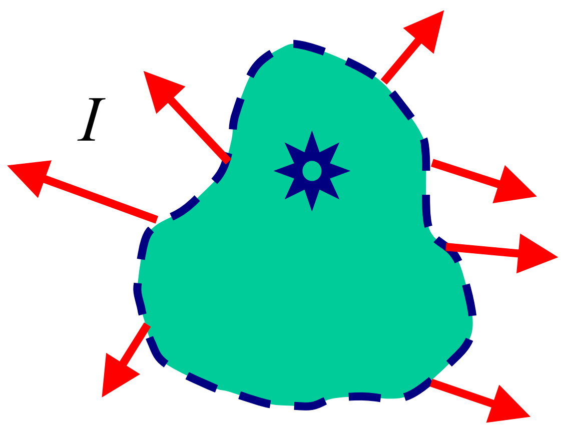
$$\vec{I} = p\vec{u}$$

- Sound intensity is the sound power radiated *per unit area*

- To get sound power, we integrate the normal component of the sound intensity over a closed surface

$$W = \int_S I_n dS$$

$$W = \int_S p(\vec{r}, t)\vec{u}(\vec{r}, t)\vec{n}dS \quad \text{(watts)}$$



# An Analogy

Like temperature, sound pressure depends on the source and the environment is it is placed in.  For example, an electric heater with a given power will raise the temperature more in a confined space than a large auditorium.

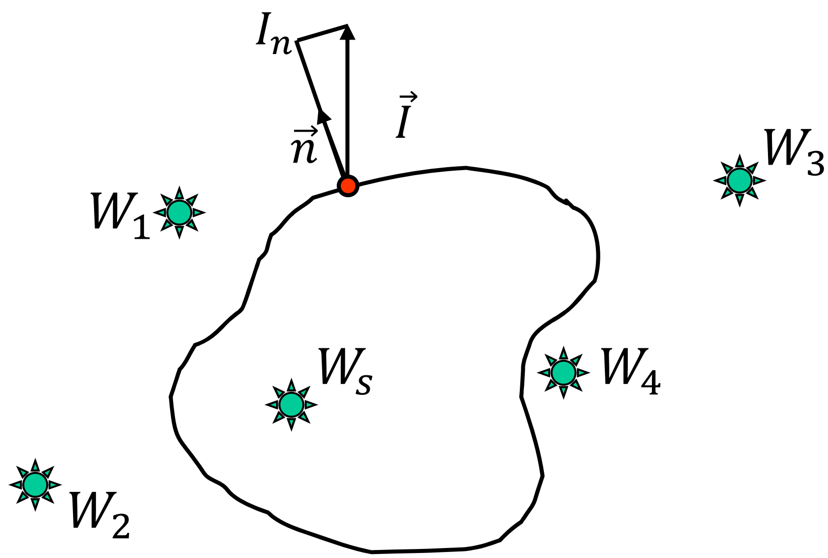
A sound source produces the same sound power (in watts) regardless of its environment*  – big or small room – but the sound pressure depends on the environment (reflectance of the walls) and the distance from the source.

* There are some notable exceptions to this (exhaust noise, close fitting enclosures)

# Source Sound Power

The sound power of a source may be found by integrating the normal component of the active sound intensity* over *any* closed contour $S$.

$$W_S = \int_S I_n dS$$

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* however, only sound pressure, not intensity, can be measured!!

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- Variability of Sound Power Measurements

# Hemispherical Free Field

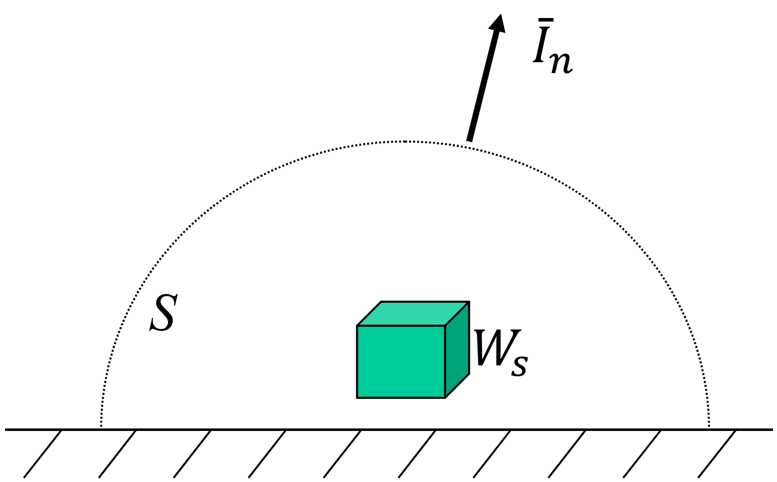
- Source is located above a hard reflecting surface
- Other sources must be removed
- Other surfaces, if any, are anechoic (totally absorbing)
- Far field sound intensity may be approximated by:

$$\bar{I}_n = \mathrm{Re}(p u_n')$$

$$u_n = \frac{p}{\rho c}$$ Far Field Assumption

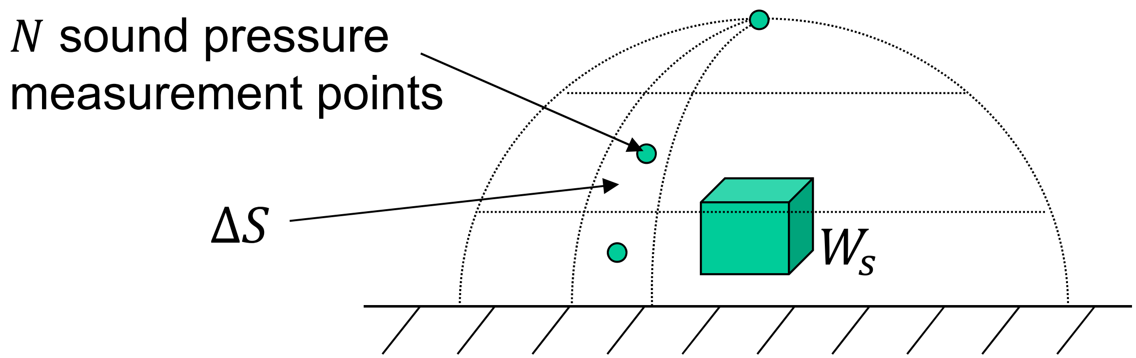
$$\bar{I}_n \approx \frac{p p'}{\rho c}$$ Far Field Intensity

$$W_S = \int_S \bar{I}_n dS \approx \int_S \frac{p^2}{\rho c} dS$$



# Hemispherical Free Field

- Divide surface $S$ into sub-areas $\Delta S$
- Measure sound pressure at a central point in each area
- Sum up mean-square sound pressures weighted by areas




$$W_S = \int_S \frac{p^2}{\rho c} dS = \frac{1}{\rho c} \sum_{i=1}^{N} p_i^2 \Delta S_i$$

$$(L_W)_{source} \approx (\bar{L}_P)_{points} + 10 \log_{10} S$$

# Example

The overall dimensions of a diesel generator set are 3 m x 1.5 m x 1.2 m (height). The measurement surface is 5 m x 3.5 m x 2.2 m. The A-Weighted sound pressure levels at 1 m from the five radiating surfaces are 100, 95, 93, 102, and 98 dBA, respectively. Assume reflected noise is minimal and evaluate the sound power level of the generator set.

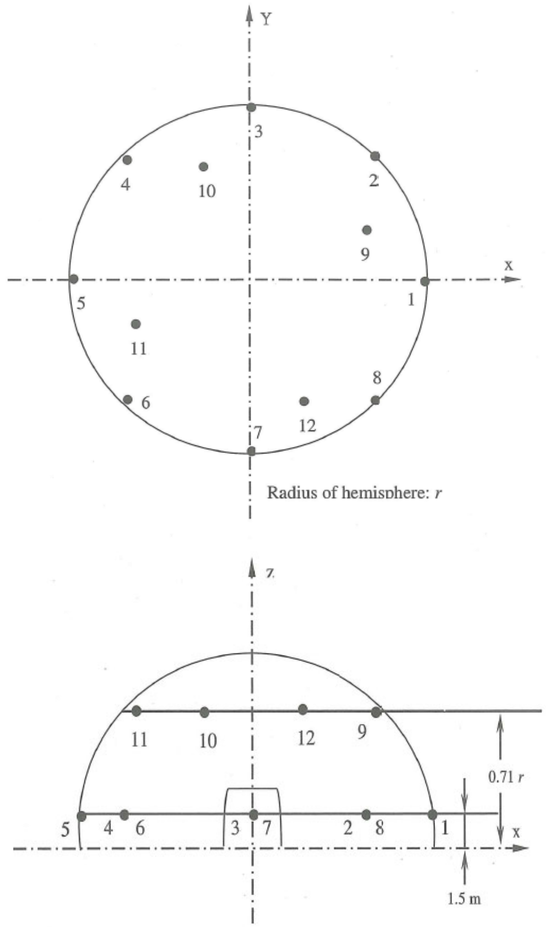
$$S = 54.9\ \mathrm{m}^2$$

$$\bar{L}_p = 10\log_{10}\left(\frac{1}{5}\left(10^{100/10} + 10^{95/10} + 10^{93/10} + 10^{102/10} + 10^{98/10}\right)\right) = 98.3\ \mathrm{dBA}$$

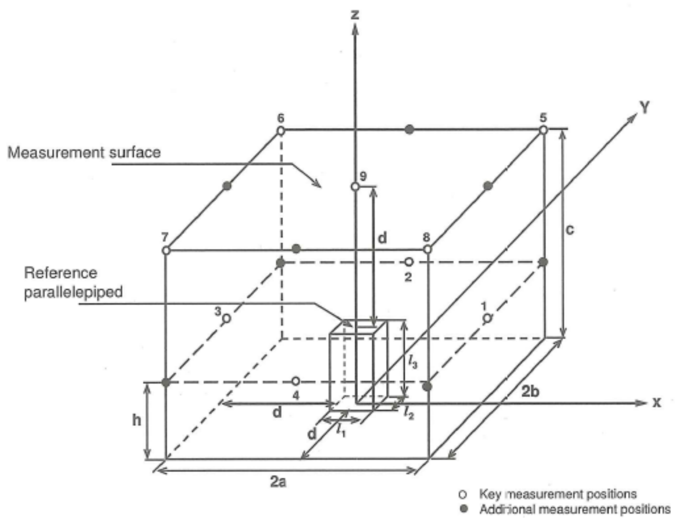
$$L_W = 98.3 + 10\log_{10}(54.9) = 115.7\ \mathrm{dBA}$$

# Standard Surfaces

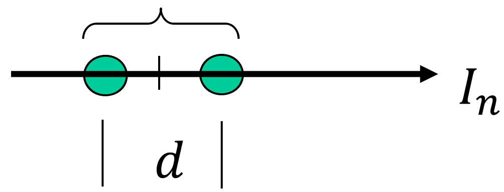
Hemispherical Surface




Parallelepiped Surface



# Sound Intensity Method




- Sound pressure is measured by two closely spaced microphones
- Sound pressure at the midpoint is approximately

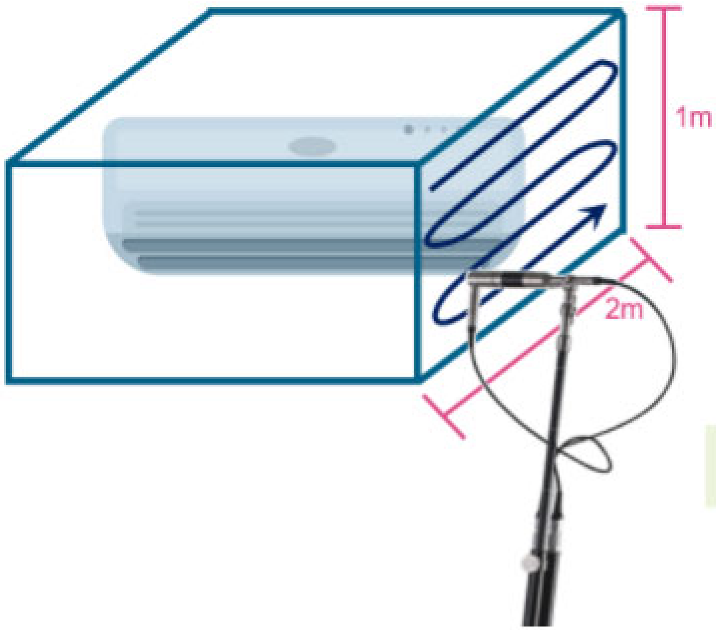
$$p \approx \frac{(p_1 + p_2)}{2}$$

- Particle velocity at the midpoint is approximately

$$u(t) = -\frac{1}{j\omega\rho_o}\frac{\partial p}{\partial n} \approx -\frac{1}{j\omega\rho_o}(p_1 - p_2)$$

where $d$ is the distance between the microphones.

# Sound Intensity Scanning




$$Sound\ intensity = 0.005\ \frac{W}{m^2}$$

$$Area = 2\ m^2$$

$$Sound\ power = Intensity * Area$$

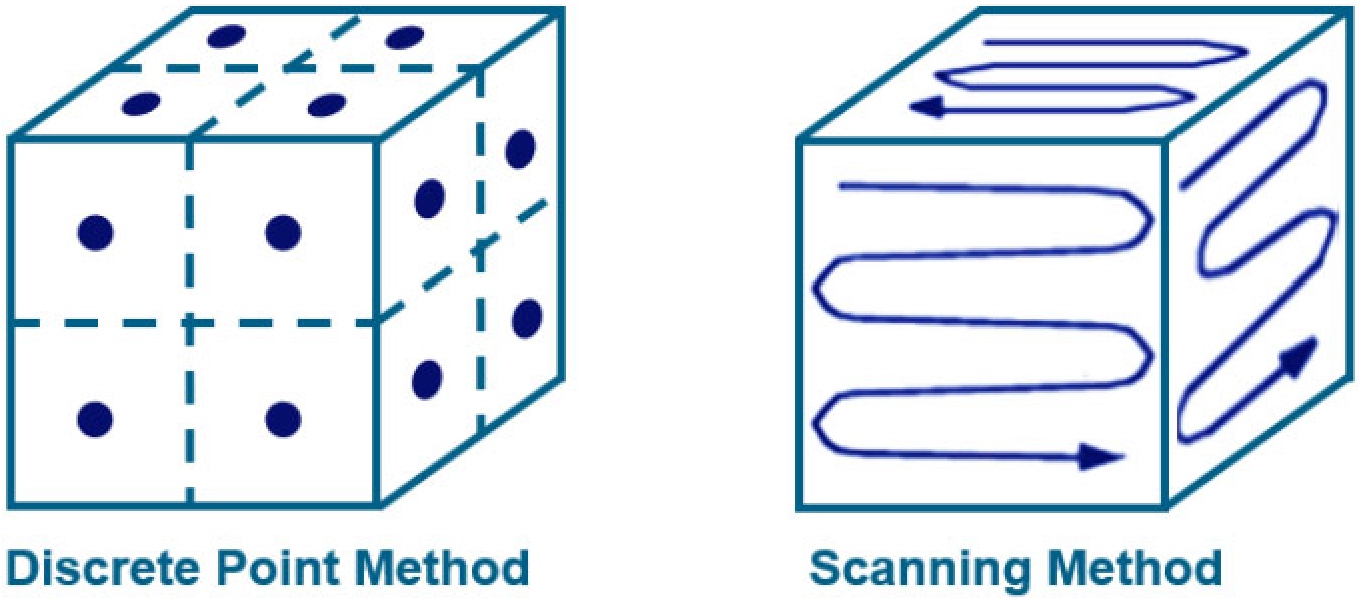
$$Sound\ power = 0.005\ \frac{W}{m^2} * 2\ m^2$$

$$Sound\ power = 0.010\ W$$

$$Sound\ power = 100\ dB\ [W]$$

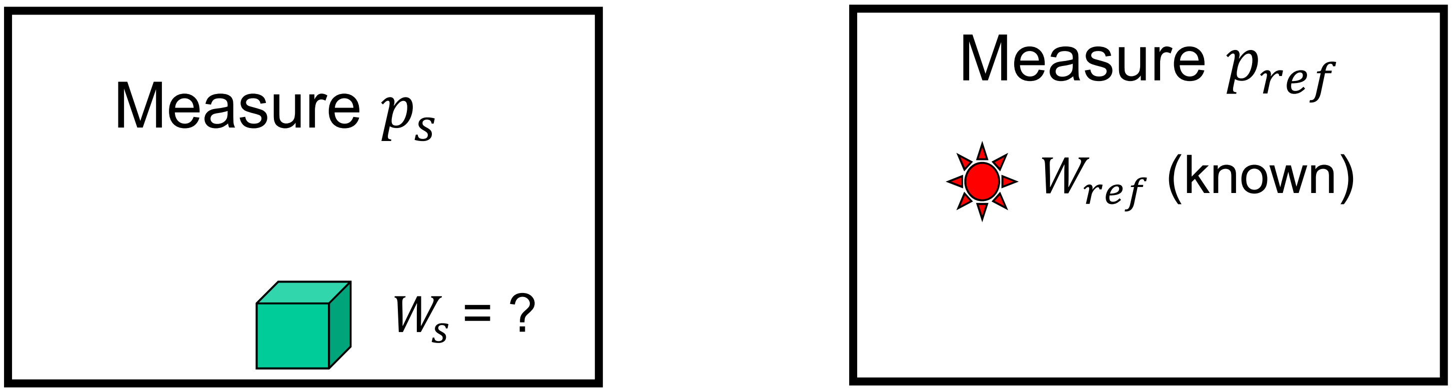
https://community.sw.siemens.com/s/article/Sound-Intensity

# Sound Intensity Scanning




https://community.sw.siemens.com/s/article/Sound-Intensity

# Comparison Method




Room or other enclosed space

$$\frac{P_{ref}^2}{W_{ref}} = \frac{p_s^2}{W_s}$$

In dB $(L_W)_{source} = (L_W)_{ref} + (L_P)_{source} - (L_P)_{ref}$

The $L_P$ measurements are made at several points and averaged

# Summary

| | Free Field | Comparison | Intensity Scan |
|---|---|---|---|
| Measurement Time | Fast | Fast | Slower |
| Repeatability | Yes | Yes | More Variation |
| Anechoic / Reverberant | Anechoic | Reverberant | Not Reverberant |

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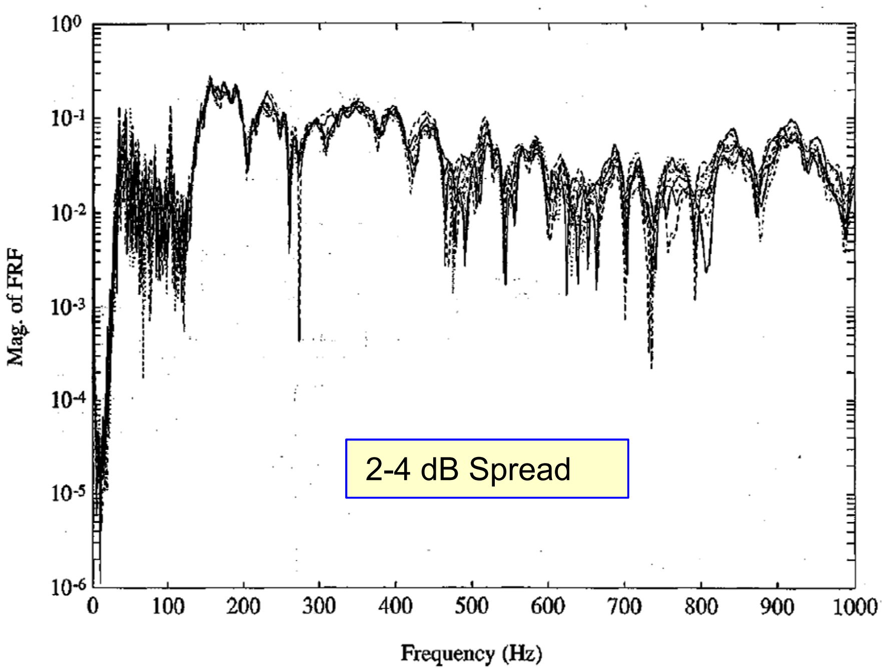
# Kompella and Bernhard (1993)

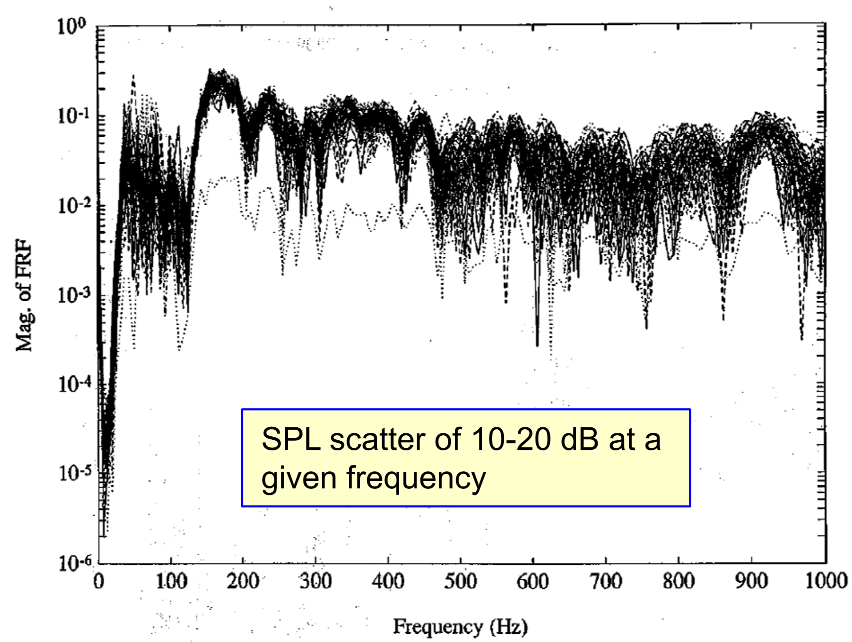
- Measured structureborne and airborne FRF's on 99 *identical* Isuzu SUV's and 57 *identical* pickup trucks.
- Excitations and receivers
  - Loudspeaker under the vehicle adjacent to left front wheel.
  - Impact hammer at location on left front wheel.
  - Microphones at driver's and passenger's ear
  - 100 averages for airborne FRF's, 10 for structureborne FRF's
- Controls
  - HVAC vents closed, keys removed, headrests pushed down, etc.
  - Valve stem in top position, tire pressure of 29 psi.
  - Attempt made to keep interior temperature constant.

# Kompella and Bernhard (1993)

Airborne FRF's
(12 Repeat Measurements)

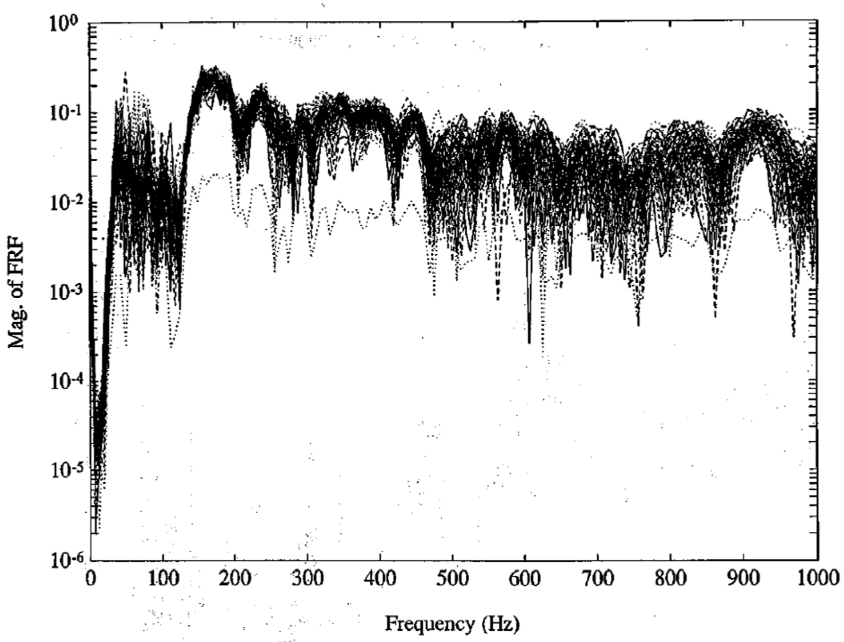



Airborne FRF's
(99 SUV Vehicles)

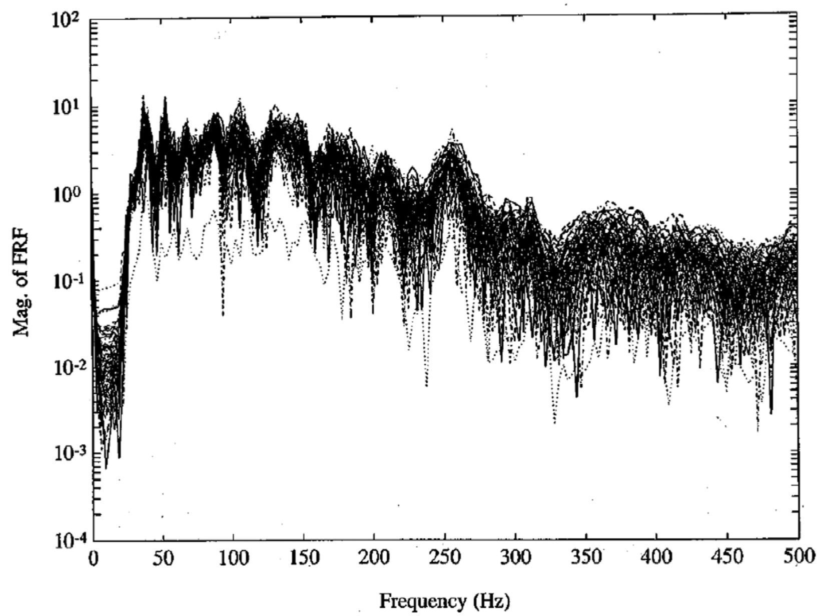


# Kompella and Bernhard (1993)

Airborne FRF's
(99 SUV Vehicles)



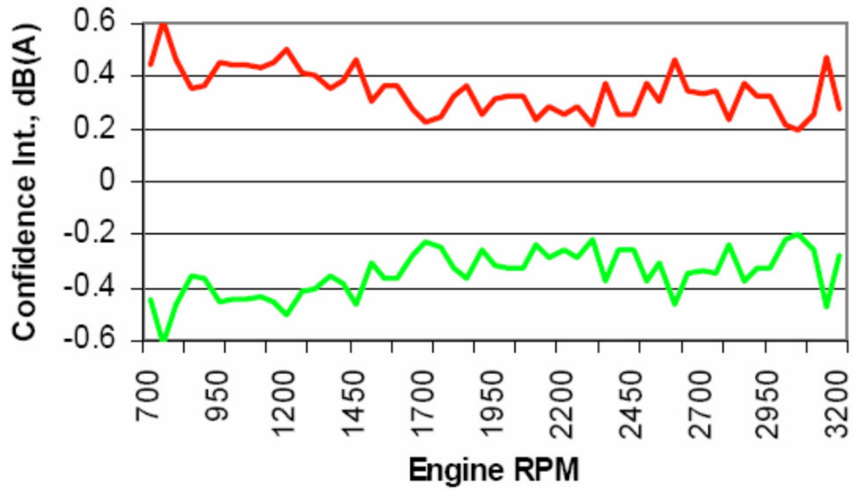

Structureborne FRF's
(99 SUV Vehicles)



# Reinhart et al. (2003)

- Variations in diesel engine populations using an approach based on SAE J1074.
- The standard deviation of 20 back-to-back full-load sweeps is as high as 0.5 dB at low RPM, but it declines to values around 0.2 dB at most speeds.

90% confidence interval for a 3 sweep average.



# Reinhart et al. (2003)

- ✓ 3 install-test-remove cycles were performed at two plants

90% confidence interval for Plant A

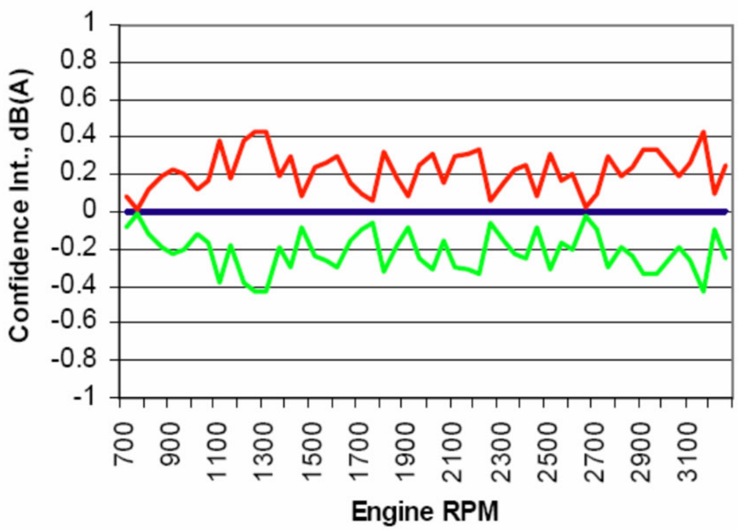



Figure 7. Confidence intervals for 3 install-test-remove cycles of a Plant A engine under full-load sweeps.

90% confidence interval for Plant B

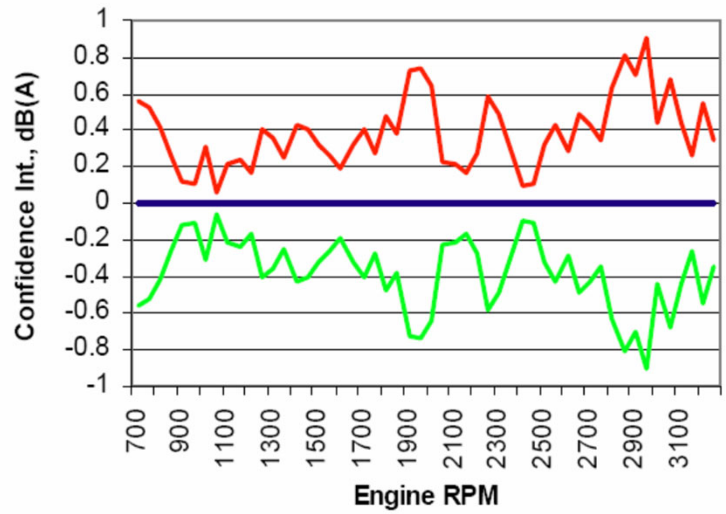



Figure 8. Confidence interval for 3 install-test-remove cycles of a Plant B engine under full-load sweeps. Note that Plant B engines show more scatter than Plant A.

# Reinhart et al. (2003)

✓ Confidence interval for populations at two plants.

90% confidence interval for Plant A

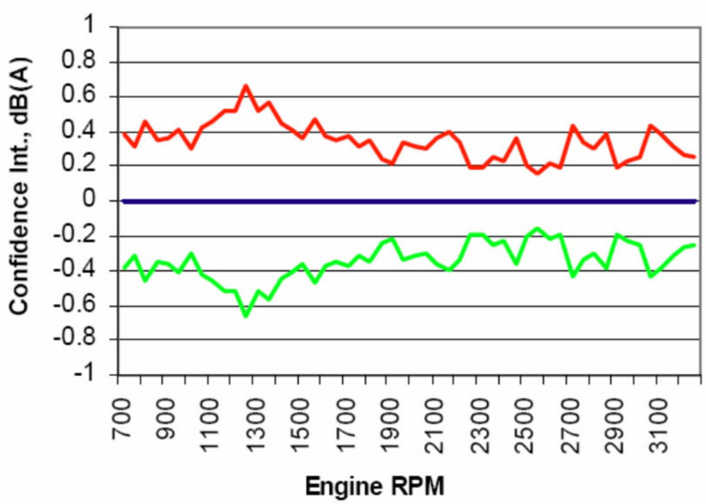



Figure 11. Confidence interval for the population of Plant A engines under full-load sweeps, based on 5 samples.

90% confidence interval for Plant B

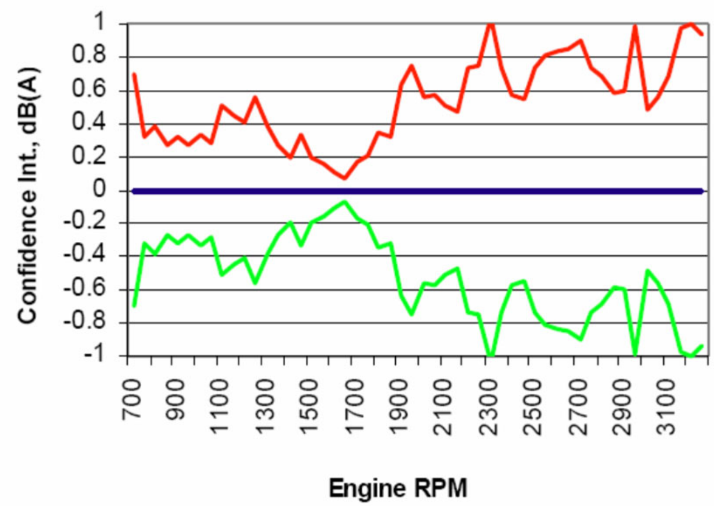


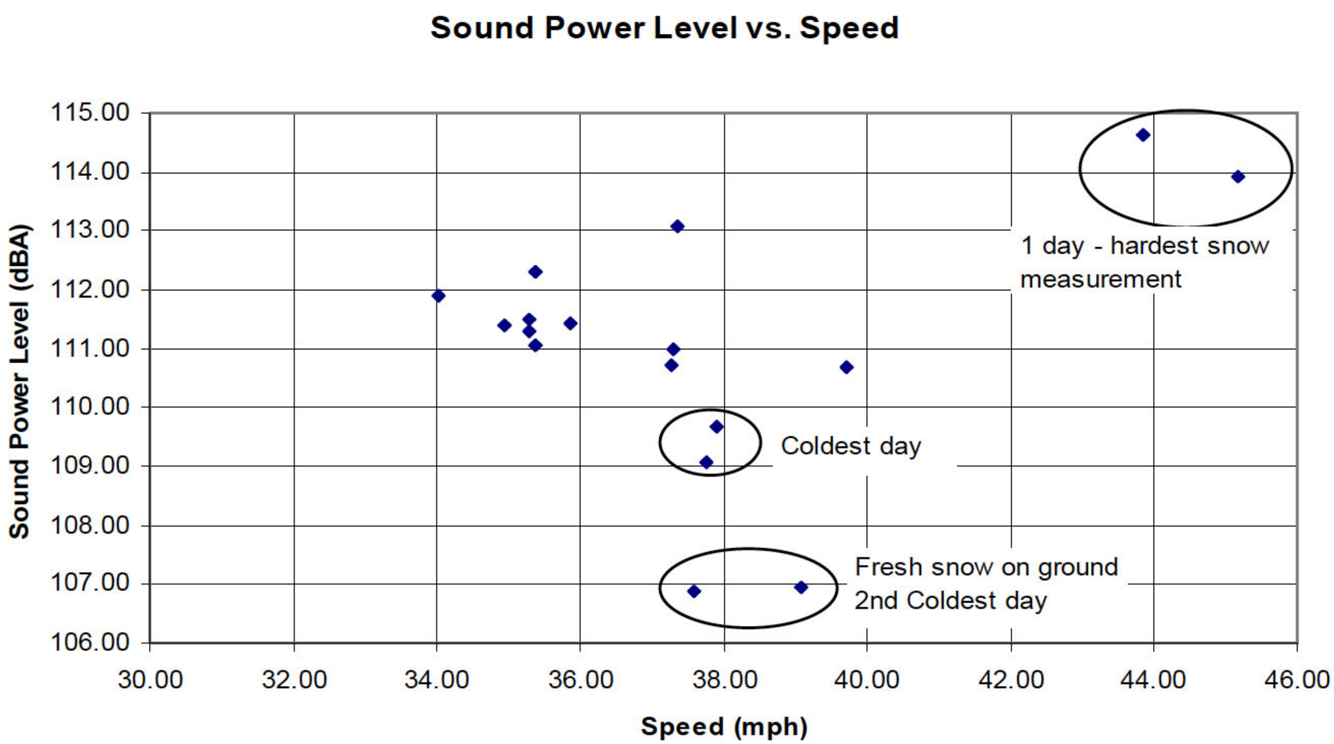

Figure 13. Confidence interval for the population of Plant B engines under full-load sweeps, based on 4 samples.

# Reinhart et al. (2003)

- ✓ "If a change is made and measured in a back-to-back test using a 3 speed sweep average, the measured difference must be greater than 0.8 dBA to be statistically significant. In other words, if the test produces a result showing a 1 dBA difference between the two configurations, there is 90% confidence that the true difference is between 0.2 and 1.8 dBA."
- ✓ "If only one engine from each, population is tested, the difference would have to be greater than 1.6 dBA to have 90% confidence that one engine population is louder than the other. A measured difference of 0.8 dBA means that there is 90% confidence that the true difference is between 0 and 1.6 dBA. This is a pretty wide window."

# Blough, Gwaltney, and Vizanko (2005)

Snowmobile constant MPH pass-by noise test (SAE-J192)



# References


- M. S. Kompella and R. J. Bernhard, Measurement of the Statistical Variation of Structural-Acoustic Characteristics of Automotive Vehicles," SAE Noise and Vibration Conference, Paper No. 931272 (1993).
- T. E. Reinhart, A. Sampath, K. S. Bagga, and G. W. Leistensnider, NVH Variations in Diesel Engine Populations, SAE Noise and Vibration Conference, Paper No. 2003-01-1723 (2003).
- J. R. Blough, G. Gwaltney, and J. Vizanko, Quantifying How the Environment Effects SAE-J192 Pass-By Noise Testing of Snowmobiles, SAE Noise and Vibration Conference, Paper No. 2005-01-2414 (2005).

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- Sound Pressure and Sound Power
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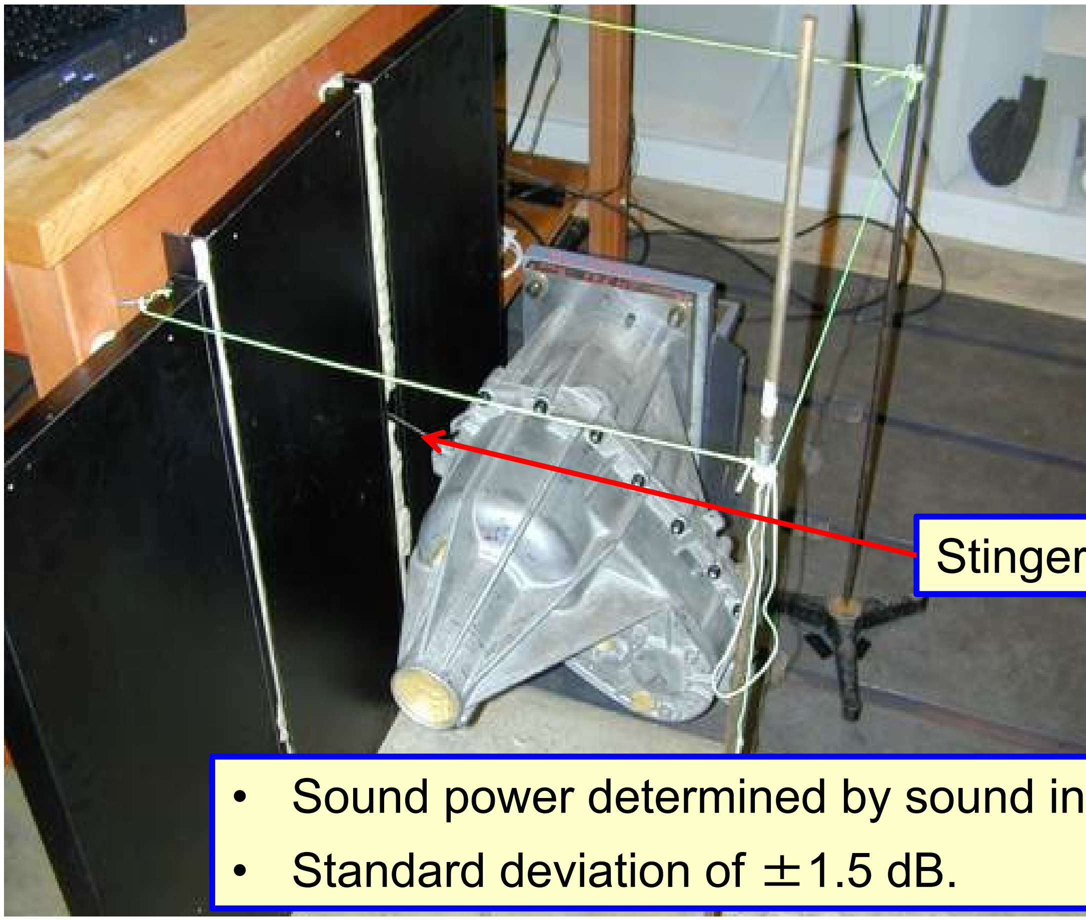
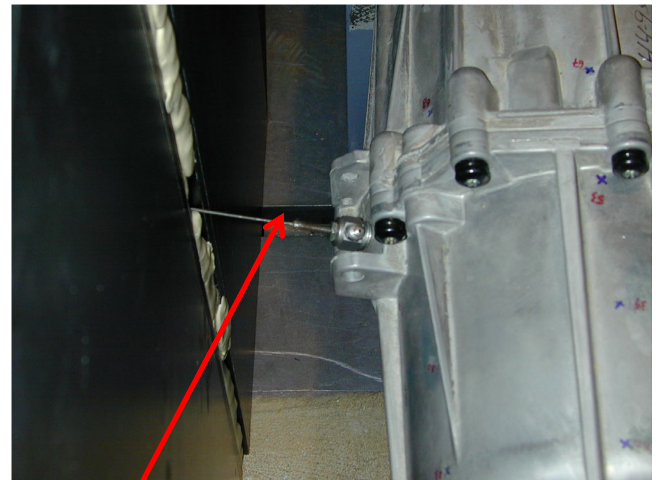
# Peppin and Putnam (2000)

Measured the sound power of 4 different reference sound sources in seven different reverberation rooms.

| Frequency (Hz) | Average Standard Deviation (dBA) |
|---|---|
| 100 | 1.77 |
| 125 | 1.03 |
| 160 | 0.57 |
| 200 | 0.59 |
| 250 | 0.45 |
| 315 | 0.49 |
| 400 | 0.48 |
| 500 | 0.51 |
| 630 | 0.51 |
| 800 | 0.65 |
| 1000 | 0.63 |
| 1250 | 0.43 |
| 1600 | 0.42 |
| 2000 | 0.70 |
| 2500 | 0.61 |
| 3150 | 0.53 |
| 4000 | 0.48 |
| 5000 | 0.43 |

# Han and Song (2006)





Stinger attached to shaker

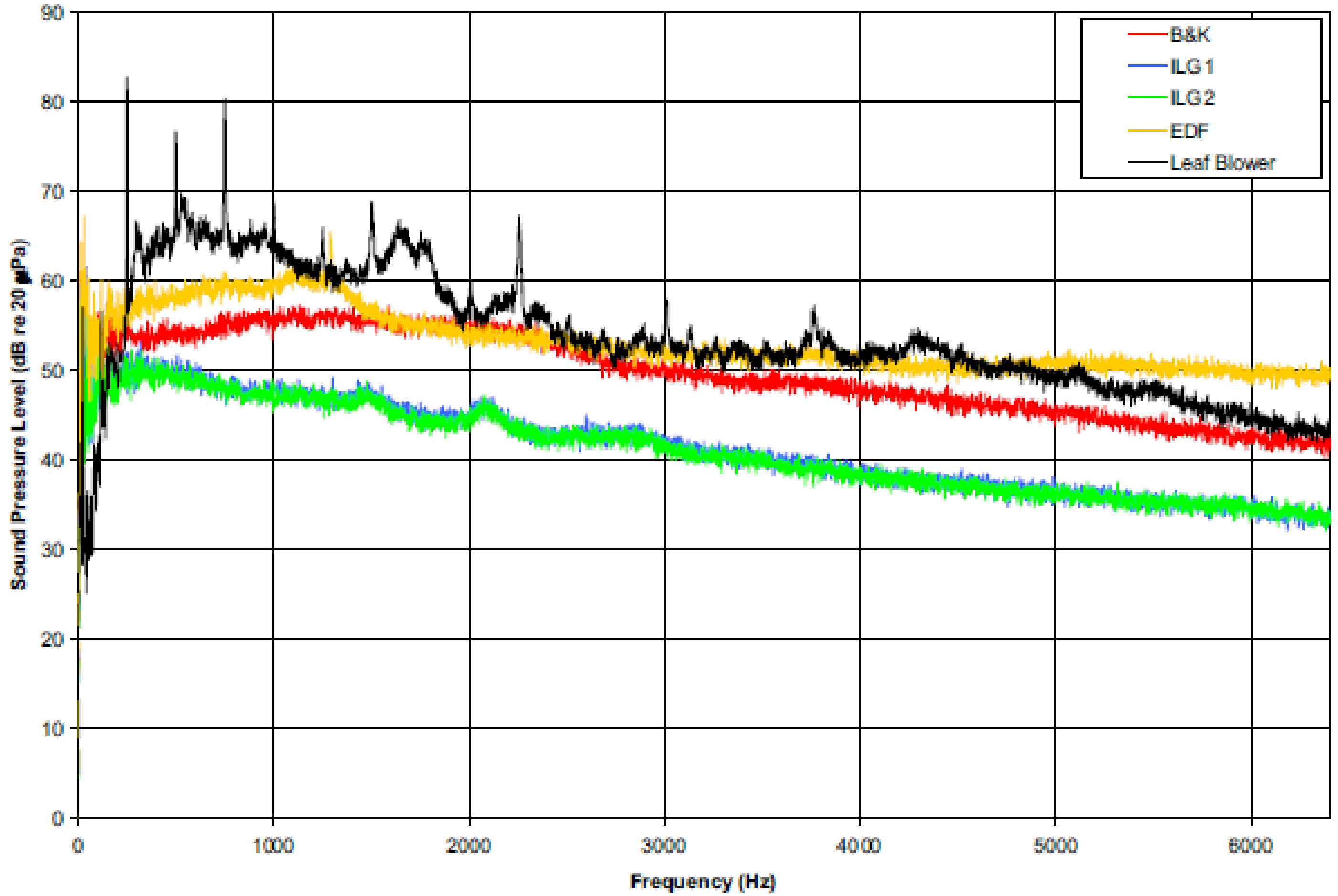
- Sound power determined by sound intensity scan (N=10).
- Standard deviation of ±1.5 dB.

# Lind (2009)

- Measured sound power of 5 sources in four reverberation rooms with volumes of 140, 280, 560, and 1790 m.
- Variables investigated included source location, source orientation, room conditions, source operating characteristics, and microphone traverse length.

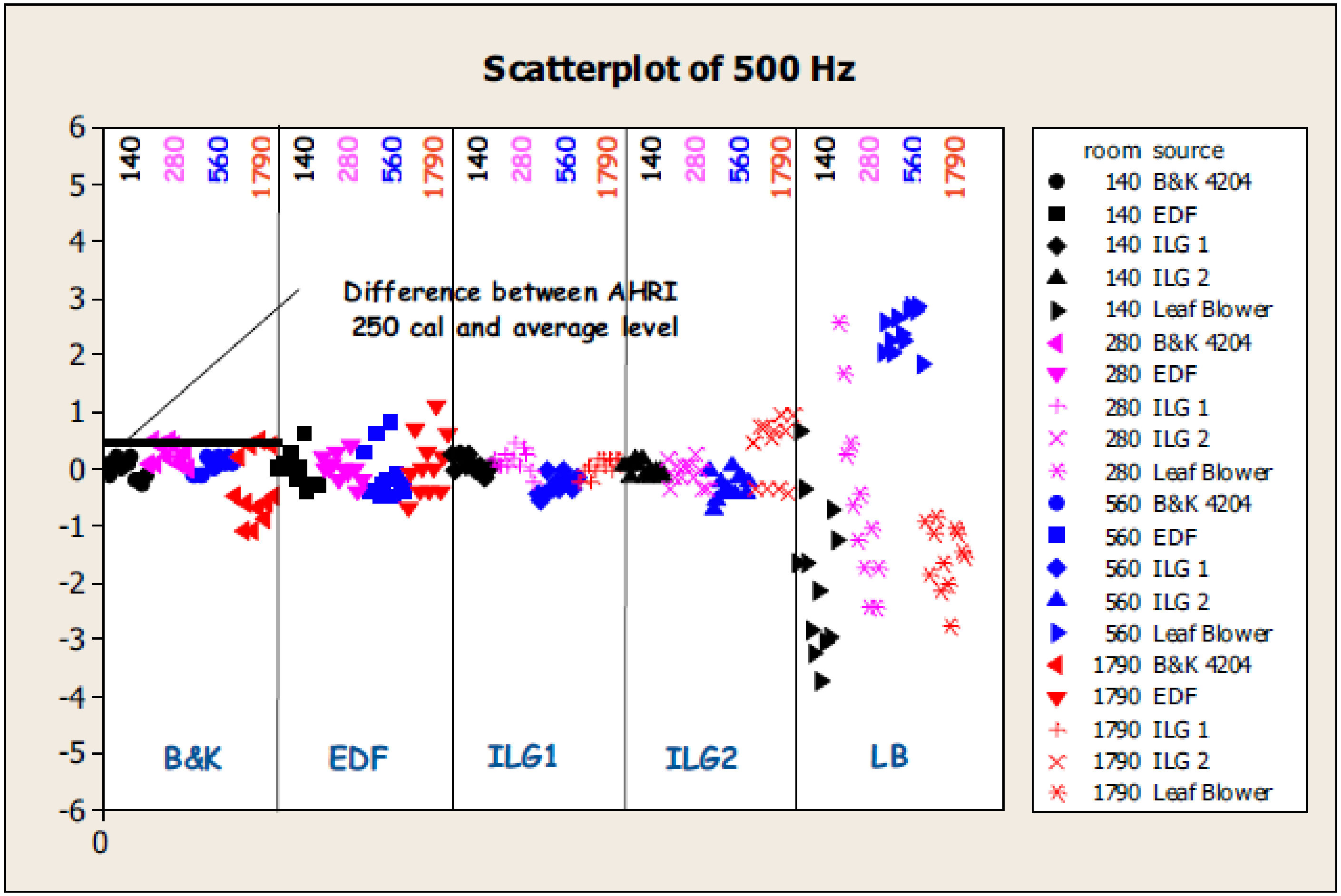
4 reference sound sources and a leaf blower

# Lind (2009)



B&K
ILG 1
ILG 2
EDF
Leaf Blower
Sound Pressure Level (dB re 20 μPa)
Frequency (Hz)
0
10
20
30
40
50
60
70
80
90
0
1000
2000
3000
4000
5000
6000

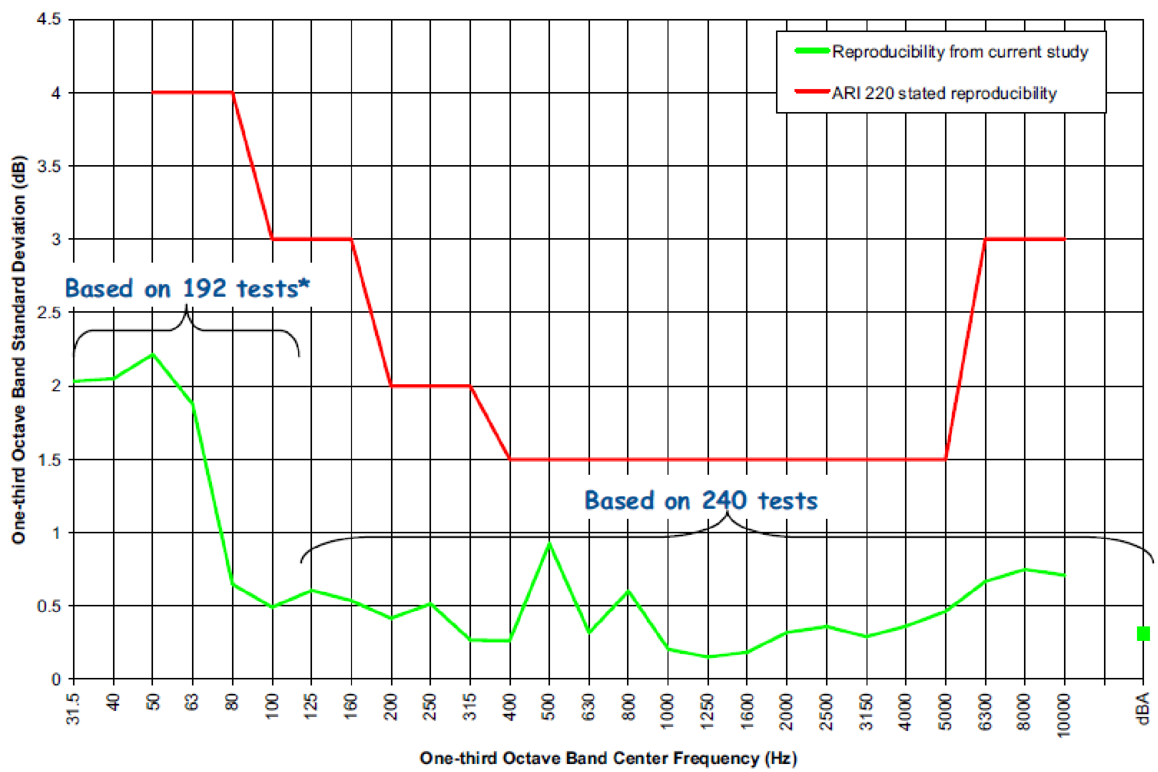
# Lind (2009)



Scatterplot of 500 Hz
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
0
140
280
560
1790
Difference between AHRI 250 cal and average level
B&K
EDF
ILG1
ILG2
LB
room source
140 B&K 4204
140 EDF
140 ILG 1
140 ILG 2
140 Leaf Blower
280 B&K 4204
280 EDF
280 ILG 1
280 ILG 2
280 Leaf Blower
560 B&K 4204
560 EDF
560 ILG 1
560 ILG 2
560 Leaf Blower
1790 B&K 4204
1790 EDF
1790 ILG 1
1790 ILG 2
1790 Leaf Blower

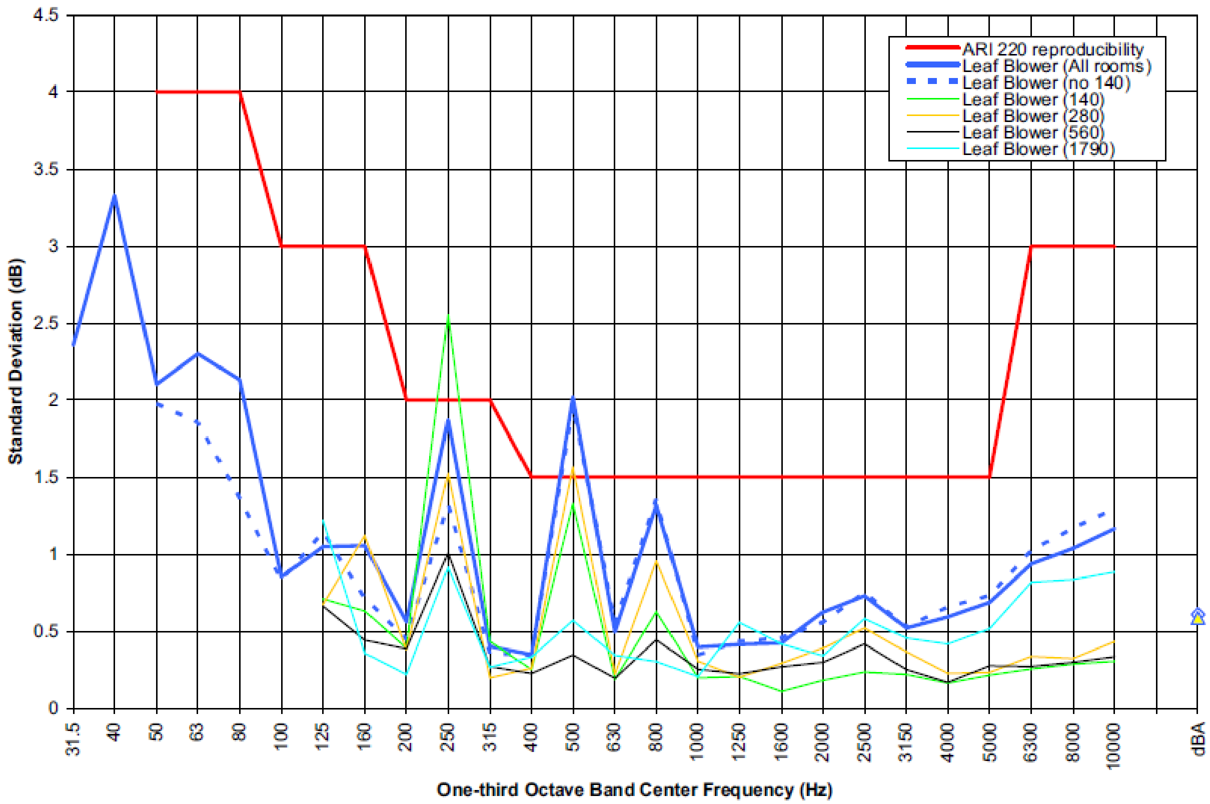
# Lind (2009)

- Reproducibility of sound power measurements following ISO 5725-2.
- Based on the 4 reference sound sources.



# Lind (2009)

- Reproducibility of sound power measurements following ISO 5725-2.
- Leaf blower results.



# References


- S. Lind, Uncertainty of Sound Power Levels Determined following Air Conditioning Heating and Refrigeration Institute Standard 220, Proceedings of Meetings on Acoustics, 158th Meeting of the Acoustical Society of America, San Antonio, TX, October 26-30 (2009).
- R. J. Peppin and R. A. Putnam, Uncertainty in Sound Power Determination and Implications for Power Plant Acoustics, Inter-Noise 2000, Nice, France, August 27-30 (2000).

# Summary

- Be careful about conclusions based on a sample of 1.
- It is a worthwhile endeavor to measure multiple machines to get a better idea of the variability of the population.
- Simulation models are often correlated to measurement, but we should not expect better correlation than the machine and measurement variability would suggest.
- Recently, some authors have suggested that it should be a goal of the designer to develop machines where NVH measurements are repeatable.

# Putnam and Peppin (2020)

The totality of these reviewed uncertainties, especially since only a small portion of the potential field of uncertainties have been considered here, should be a warning to all acoustical professionals and analysts … So, approach the work with care and humility.