July 15, 2021

Notes on Radiation Efficiency

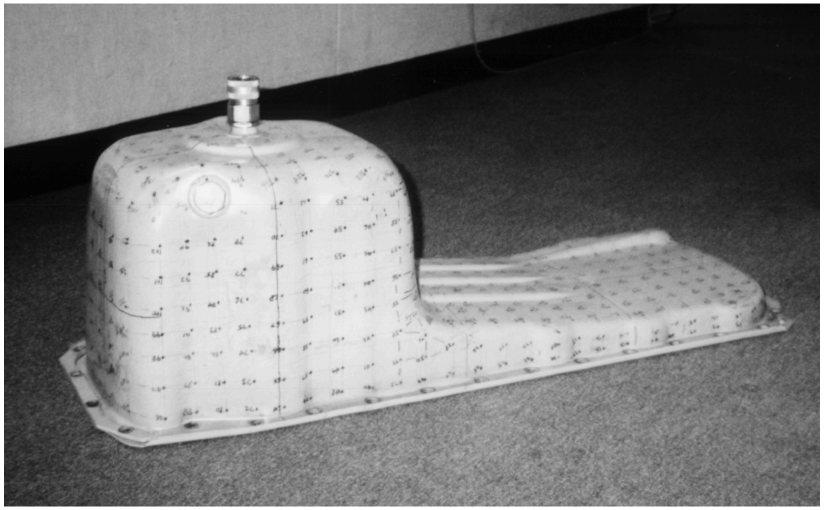
David Herrin
University of Kentucky

Vibro-Acoustics Consortium

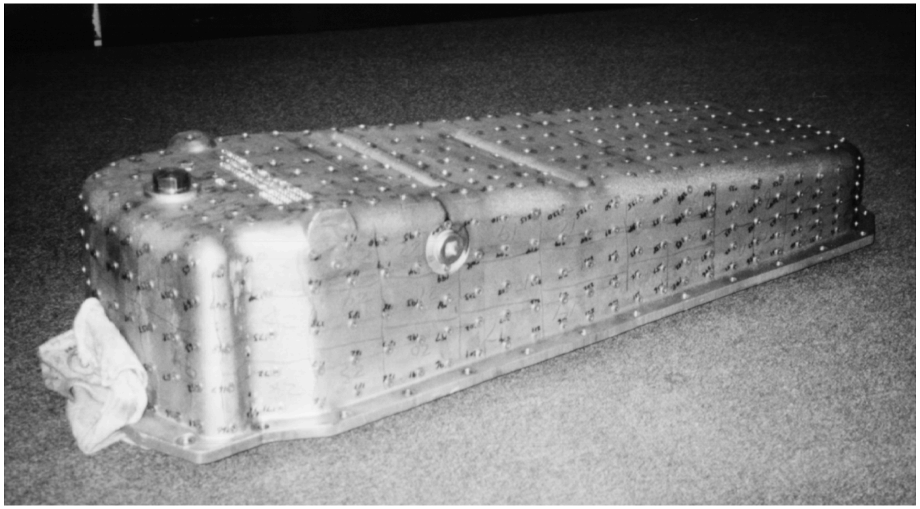
Overview

- Definition / Importance
- Example – Diesel Engine
- Measurement

Example



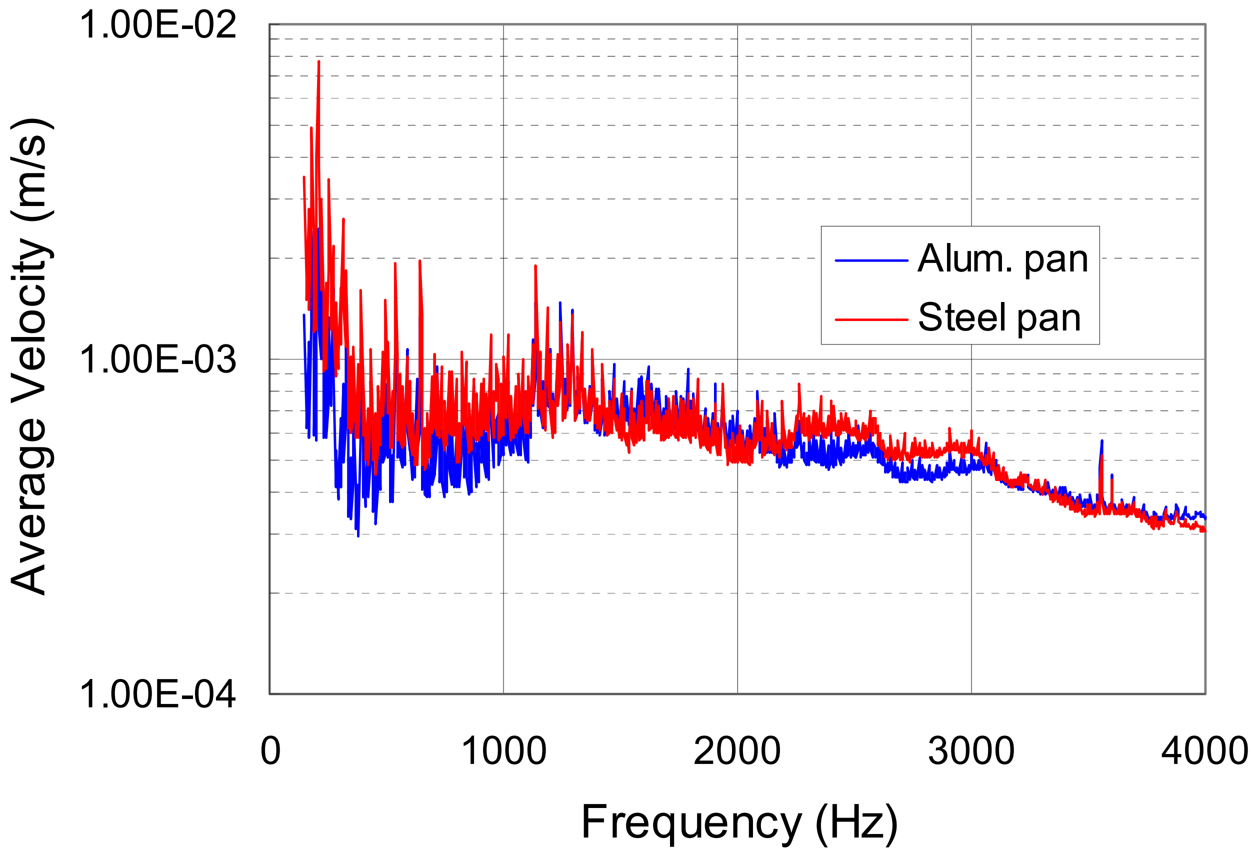
Stamped Steel Oil Pan (0.21 cm)



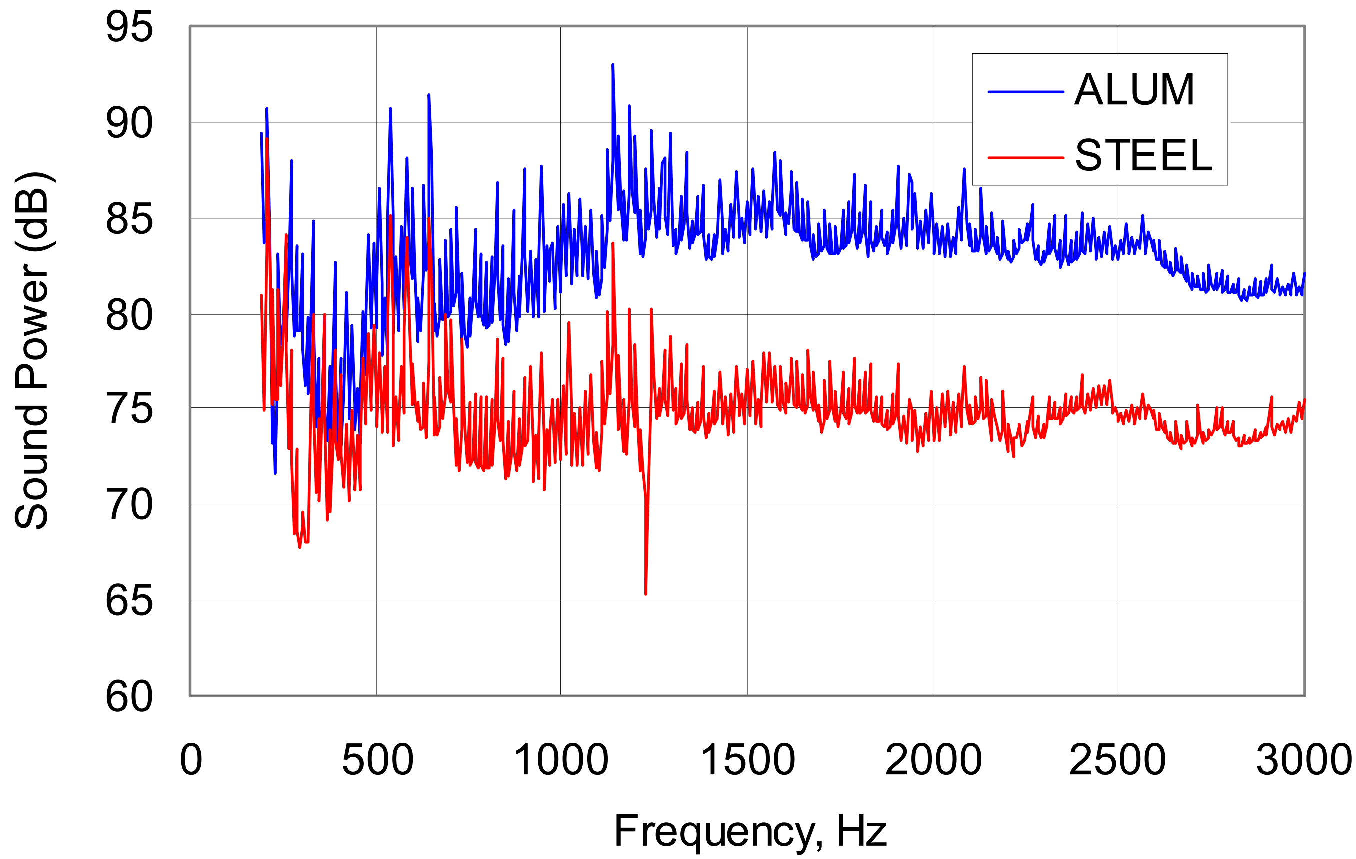
Sand-Cast Aluminum Oil Pan (1.07 cm)

Seybert, Hamilton, and Hayes (1988)

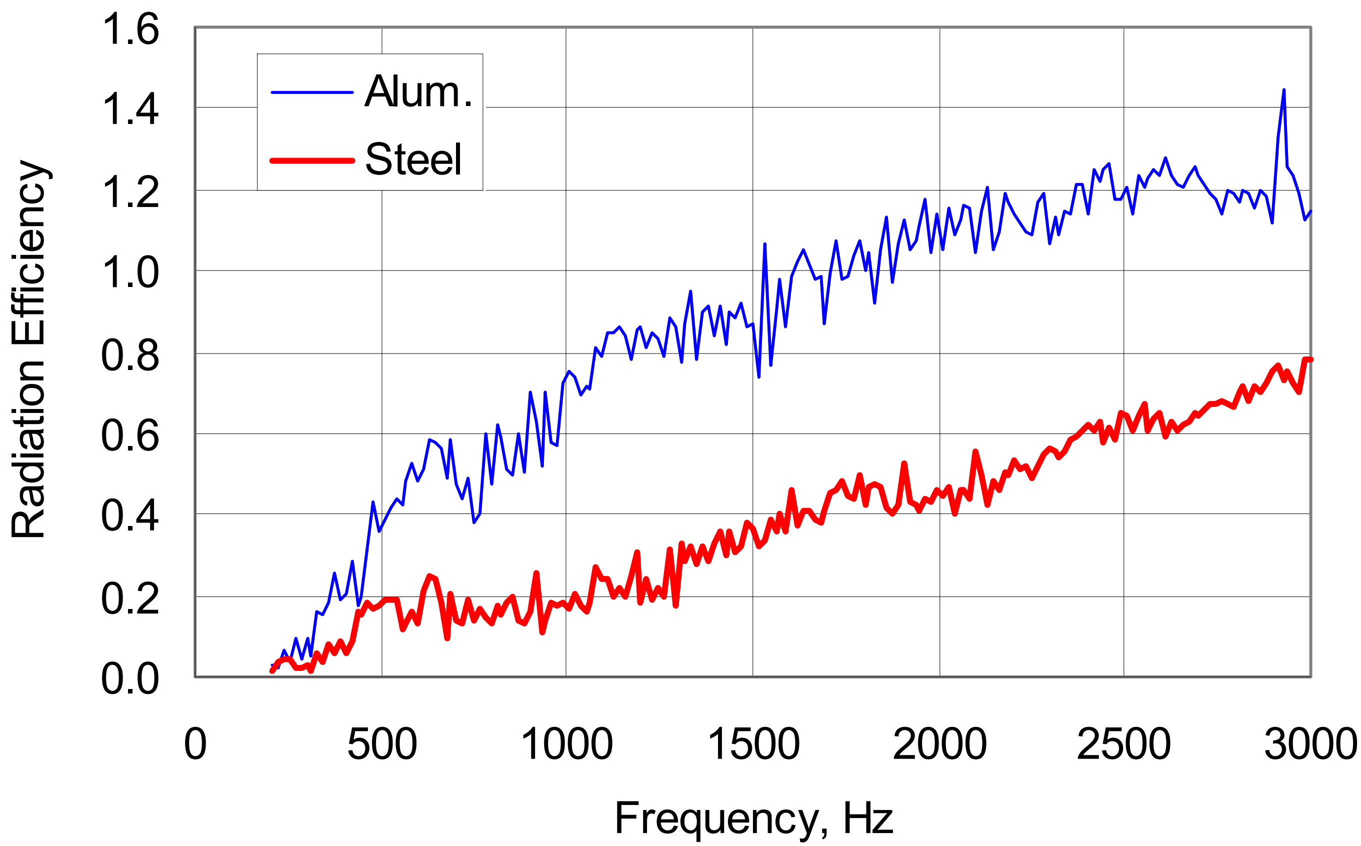
Average Vibration



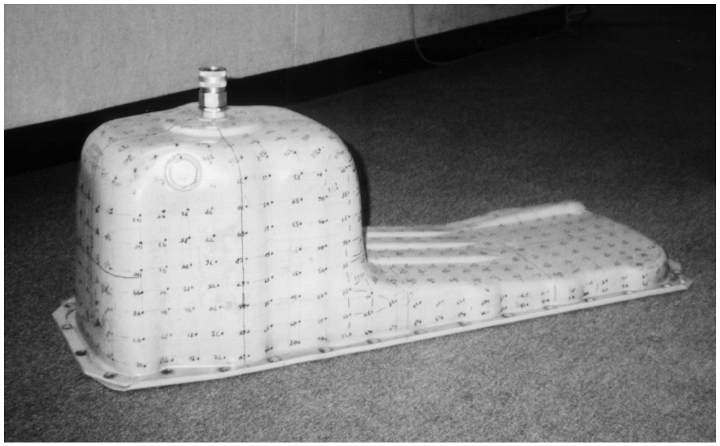
Sound Power Contribution



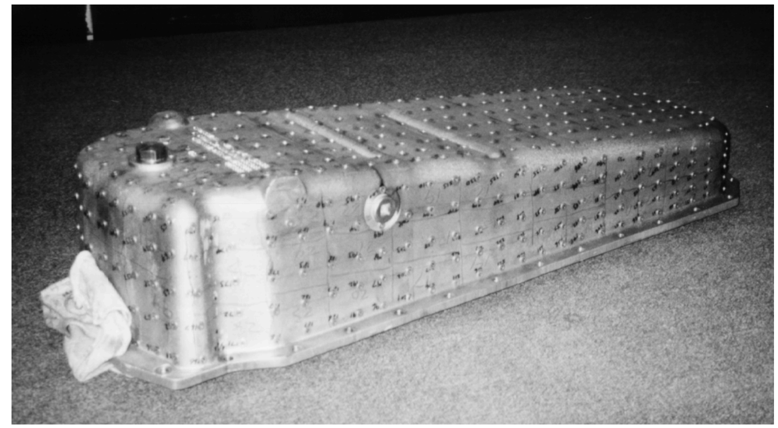
Radiation Efficiency



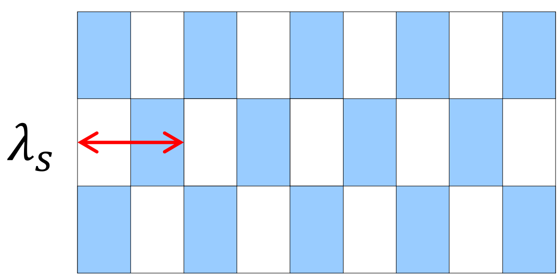
Oil Pan Comparison



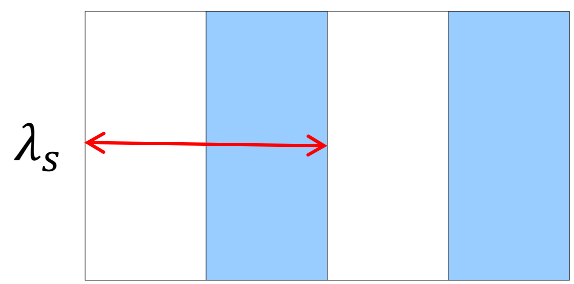
Stamped Steel Oil Pan (.084")



Sand-Cast Aluminum Oil Pan (0.42")

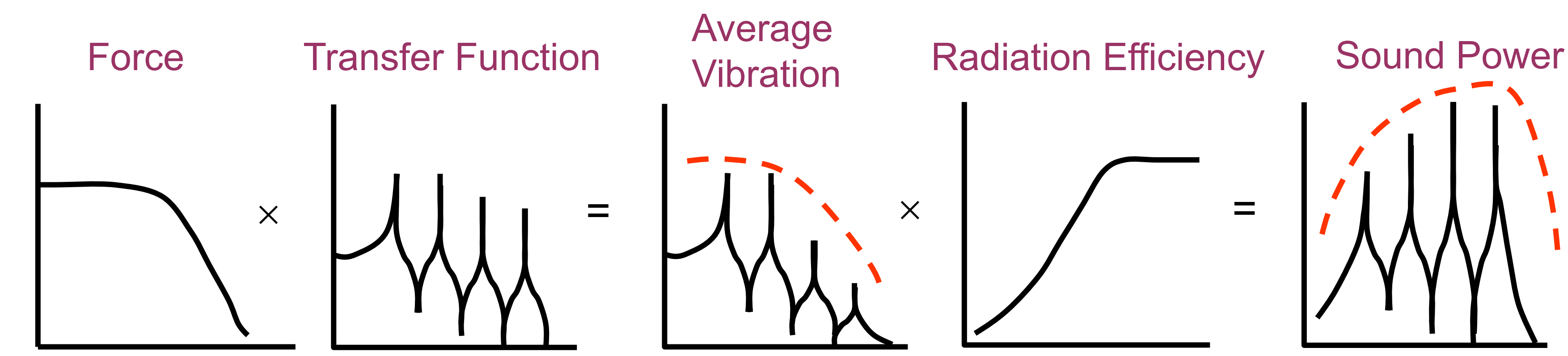


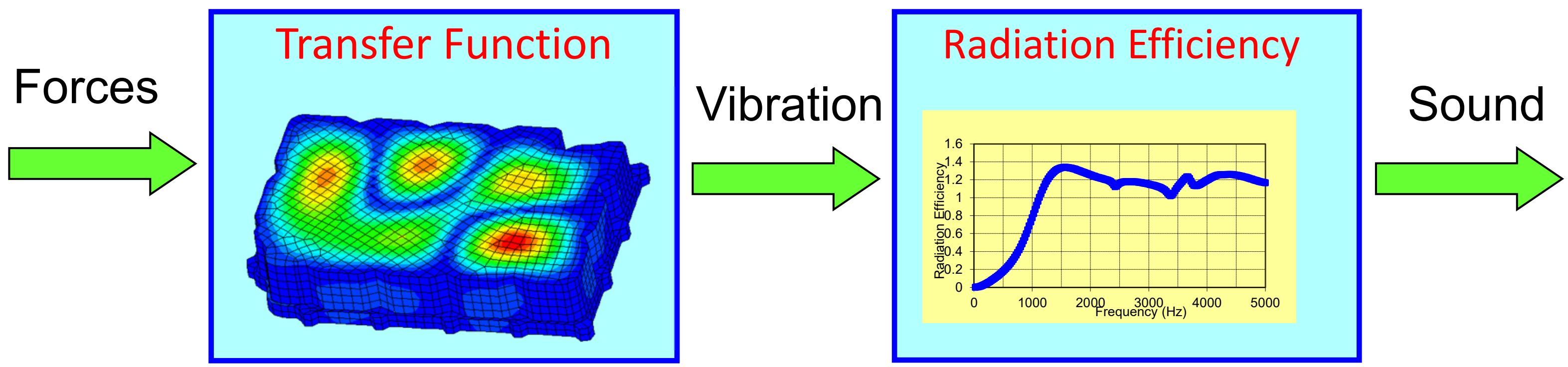
2040 Hz



2199 Hz

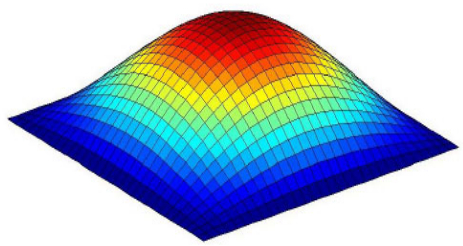
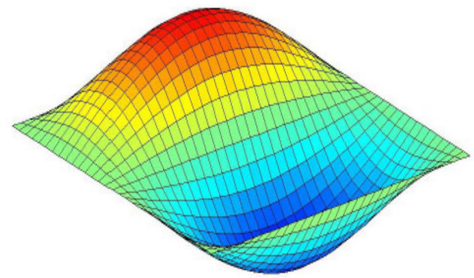
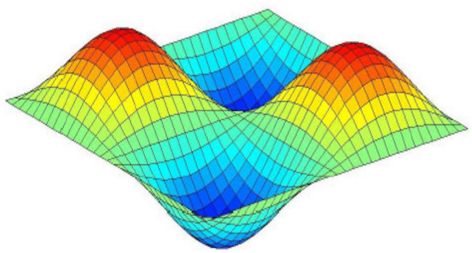
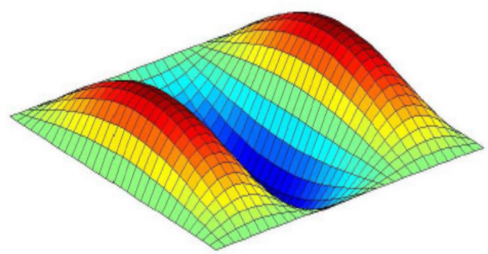
Radiation Efficiency



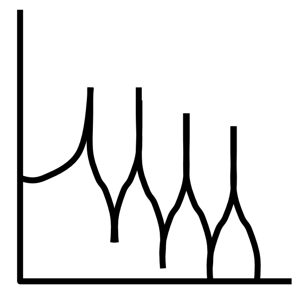


Transfer Function Panel Modes

First 4 modes of a 76 cm square steel plate which is 0.32 cm thick.

Index	$N_x = 1, N_y = 1$	$N_x = 2, N_y = 1$
Mode shape		
Frequency	25.5 Hz	63.7 Hz
Index	$N_x = 2, N_y = 2$	$N_x = 1, N_y = 3$
Mode shape		
Frequency	101.9 Hz	127.4 Hz

Transfer Function



Transfer Function Panel Modes

Table 8-8 Eigenfrequencies of rectangular plates with certain boundary conditions. The mode's indices (m,n) represent the number of displacement antinodes projected along the short sides (m) and the long sides (n) of the plate, respectively; see figure 8-31. (Source: Based on R D Blevins, Formulas for Natural Frequency and Mode Shape. 1979. Van Nostrand Reinhold.)

Edge Conditions	a/b	μ_{mn} (m,n)				
F = Free	0.4	3.46 (1,3)	5.29 (2,2)	9.62 (1,4)	11.4 (2,3)	18.8 (1,5)
	2/3	8.95 (2,2)	9.60 (1,3)	20.7 (2,3)	22.4 (3,1)	25.9 (1,4)
	1	13.5 (2,2)	19.8 (1,3)	24.4 (3,1)	35.0 (3,2)	35.0 (2,3)
	1.5	20.1 (2,2)	21.6 (3,1)	46.6 (3,2)	50.3 (1,3)	58.2 (4,1)
	2.5	21.6 (3,1)	33.0 (2,2)	60.1 (4,1)	71.5 (3,2)	117.5 (5,1)
S = Simply Supported	0.4	11.4 (1,1)	16.2 (1,2)	24.1 (1,3)	35.1 (1,4)	41.1 (2,1)
	2/3	14.3 (1,1)	27.4 (1,2)	43.9 (2,1)	49.4 (1,3)	57.0 (2,2)
	1	19.7 (1,1)	49.4 (2,1)	49.4 (1,2)	79.0 (2,2)	98.7 (3,1)
	1.5	32.1 (1,1)	61.7 (2,1)	98.7 (1,2)	111.0 (3,1)	128.3 (2,2)
	2.5	71.6 (1,1)	101.2 (2,1)	150.5 (3,1)	219.6 (4,1)	256.6 (1,2)
C = Clamped (Fixed)	0.4	23.6 (1,1)	27.8 (1,2)	35.4 (1,3)	46.7 (1,4)	61.6 (1,5)
	2/3	27.0 (1,1)	41.7 (1,2)	66.1 (2,1)	66.6 (1,3)	79.8 (2,2)
	1	36.0 (1,1)	73.4 (2,1)	73.4 (1,2)	108.3 (2,2)	131.6 (3,1)
	1.5	60.8 (1,1)	93.7 (2,1)	148.8 (1,2)	149.7 (3,1)	179.7 (2,2)
	2.5	147.8 (1,1)	173.9 (2,1)	221.5 (3,1)	291.9 (4,1)	384.7 (5,1)

The eigenfrequencies are calculated from the table parameters, geometric data and material data using the formula

$$f_{m,n} = \frac{\mu_{mn}}{2\pi a^2}\sqrt{\frac{Eh^2}{12\rho(1-\upsilon^2)}} .$$

Here, a is the length of a long edge, h the plate thickness, ρ the plate density, E the elastic modulus and υ Poisson's ratio.

Radiation Efficiency Definition

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

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

Stated another way

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

$$L_W = 10 \log_{10}\langle \bar{u}^2 \rangle + 10 \log_{10} S + 10 \log_{10} \sigma_{rad} + 146$$

Radiation Efficiency Wavelength

In thin plates, the dominating vibration will be bending vibration.

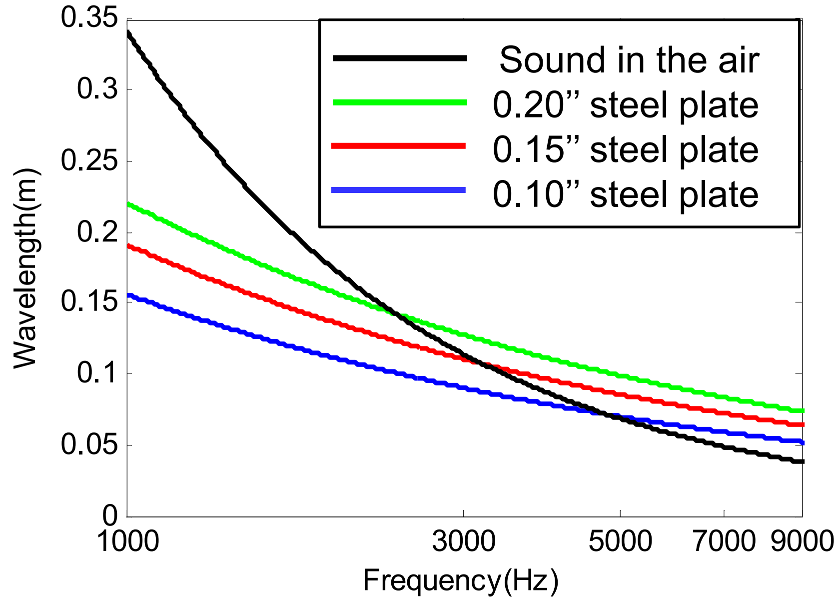
Plate Bending Wavelength

$$D = \frac{Eh^3}{12(1-\nu^2)}$$

$$c_p = \sqrt[4]{\frac{D\omega^2}{\rho_S}} \qquad \lambda_p = \sqrt{\frac{2\pi}{f}}\sqrt[4]{\frac{D}{\rho_S}}$$

Acoustic Wavelength

$$\lambda_a = \frac{c}{f}$$

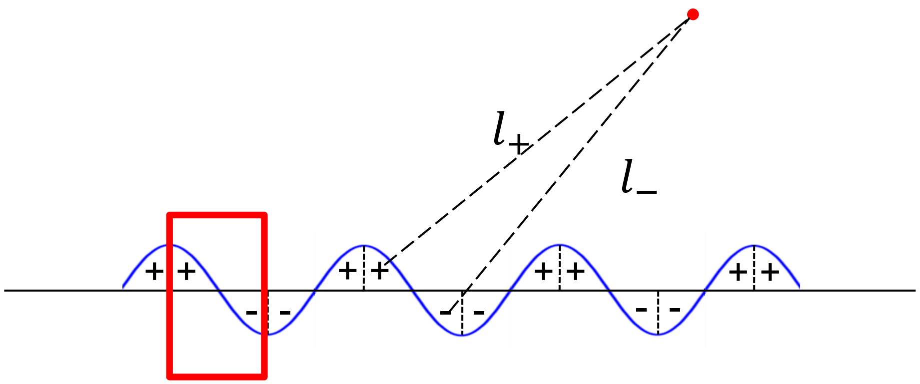


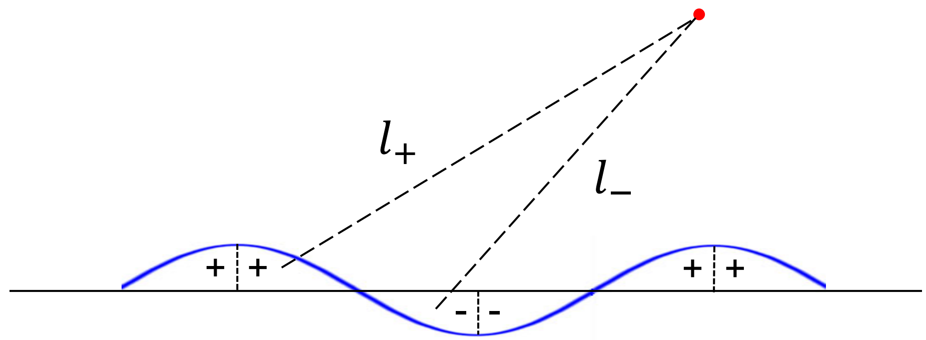
Radiation Efficiency

$\lambda_p \ll \lambda_a \qquad \Delta l = l_+ - l_- \approx 0$

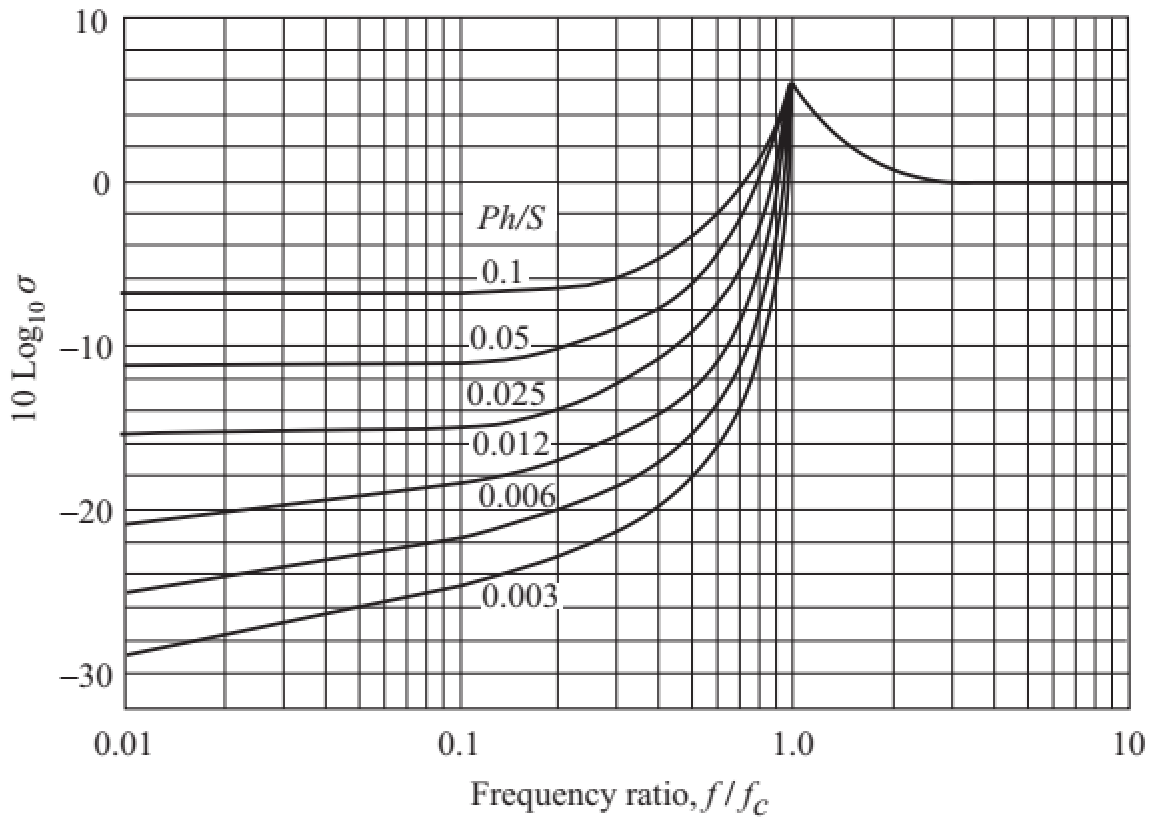
$\lambda_p \approx \lambda_a \qquad \Delta l \gg 0$

The plate will perform like closely distributed out-of-phase sources.





Radiation Efficiency Flat Aluminum Panel



P panel perimeter
h panel thickness
S panel surface area

Radiation Efficiency Critical Frequency

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{\rho_s}{D}}$$

where:

$\rho_s = \dfrac{m}{S}$ Panel surface density

$D = \dfrac{Eh^3}{12(1-\nu^2)}$ Flexural rigidity of plate

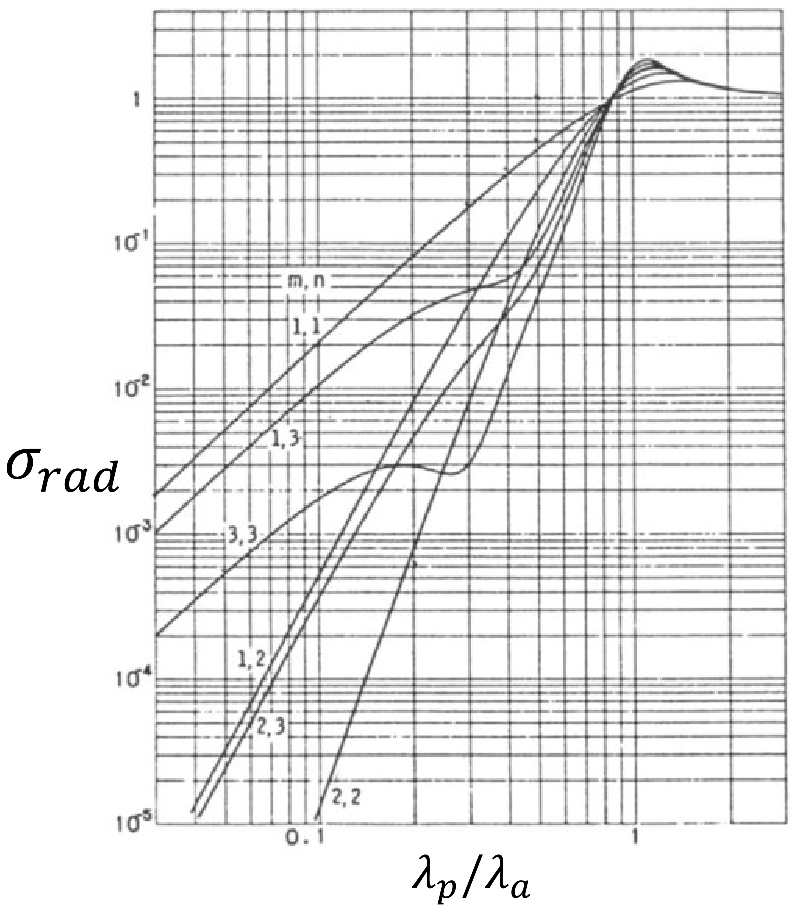
If the stiffness is decreased

$$L_W = 10\log_{10}\langle\bar{u}^2\rangle + 10\log_{10} S + 10\log_{10}\sigma_{rad} + 146$$

Wallace, 1972

July 15, 2021

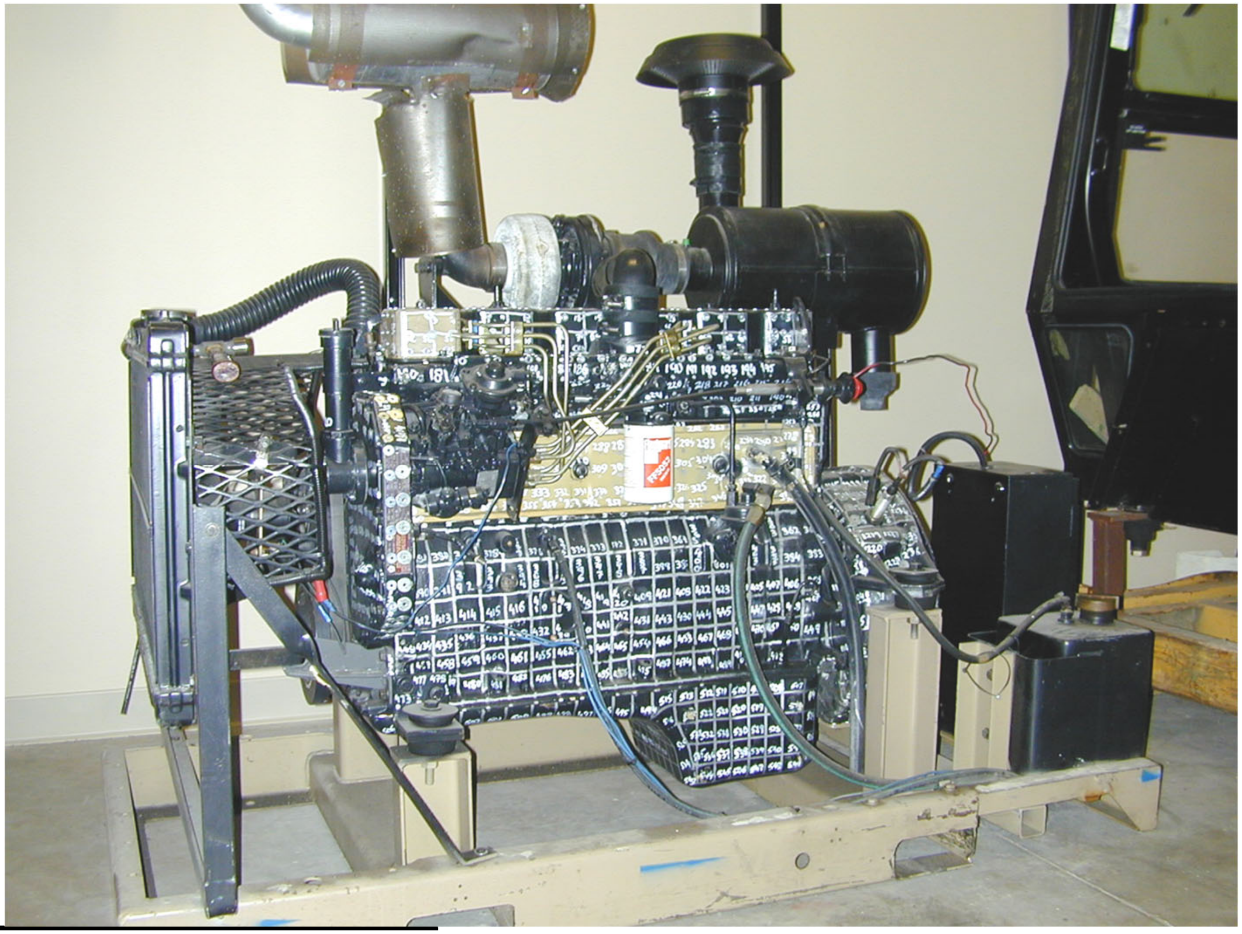
Radiation Efficiency Plate Modes



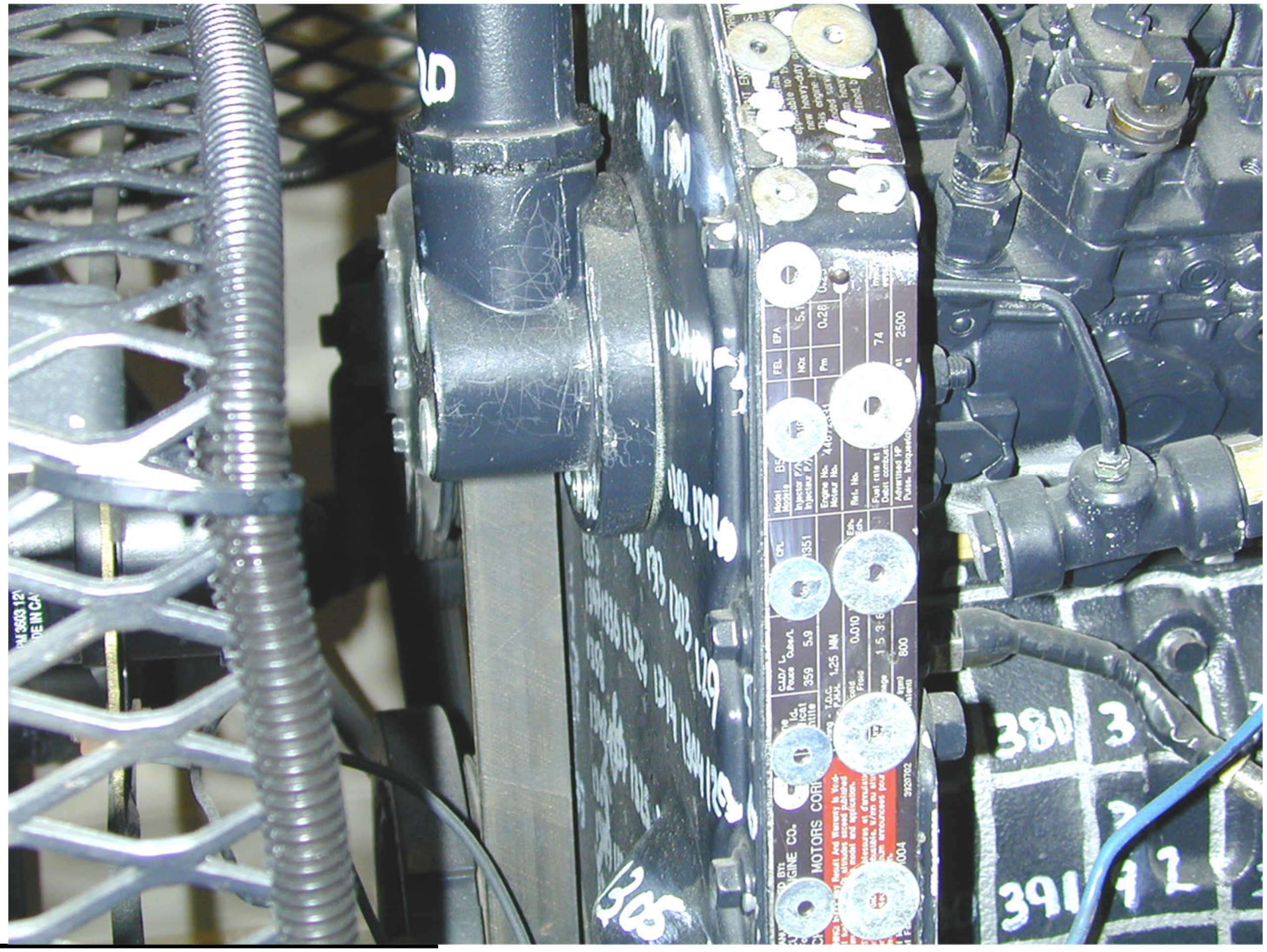
Overview

- Definition / Importance
- Example – Diesel Engine
- Measurement

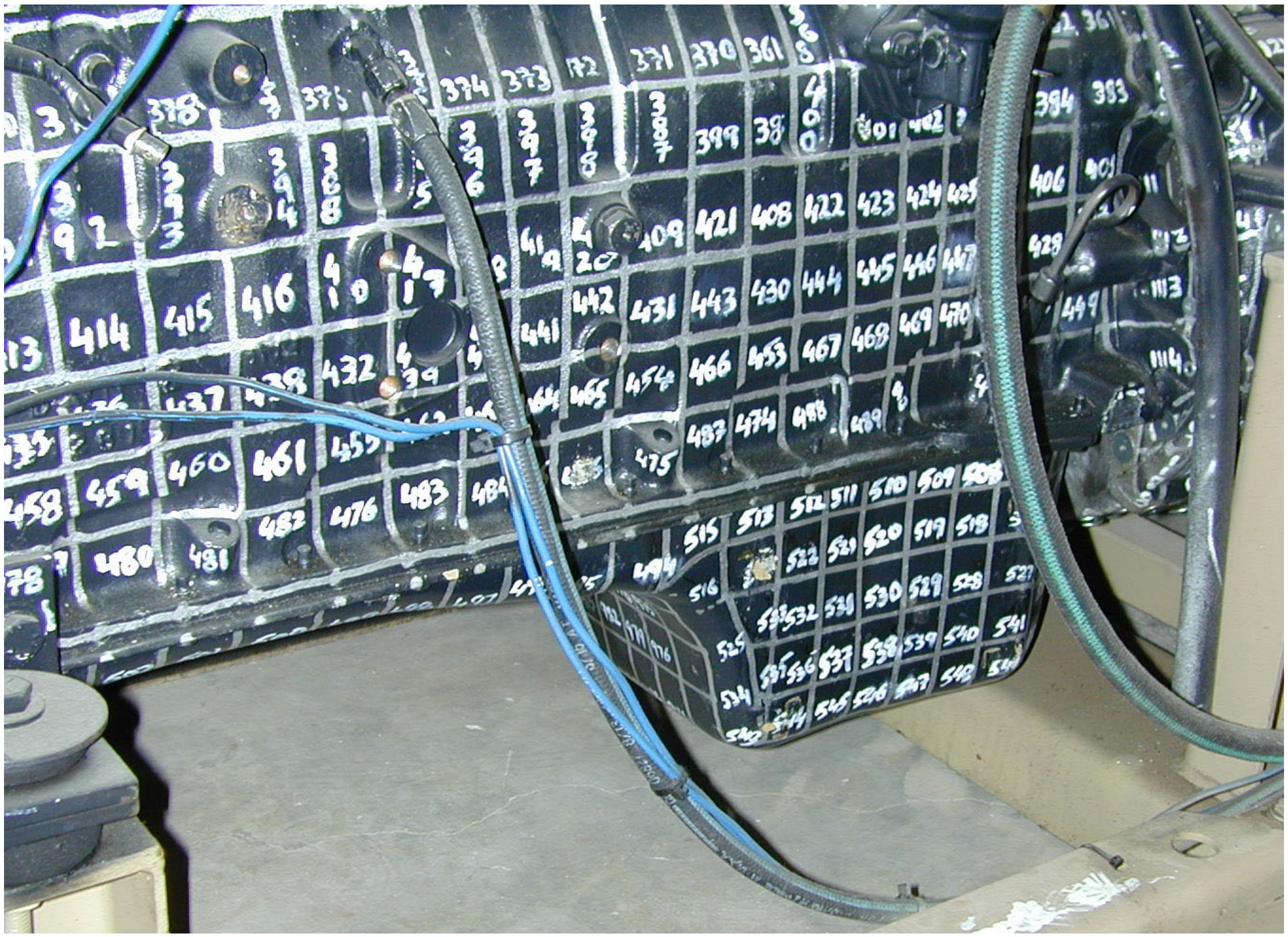
Diesel Engine



Front Cover



Oil Pan



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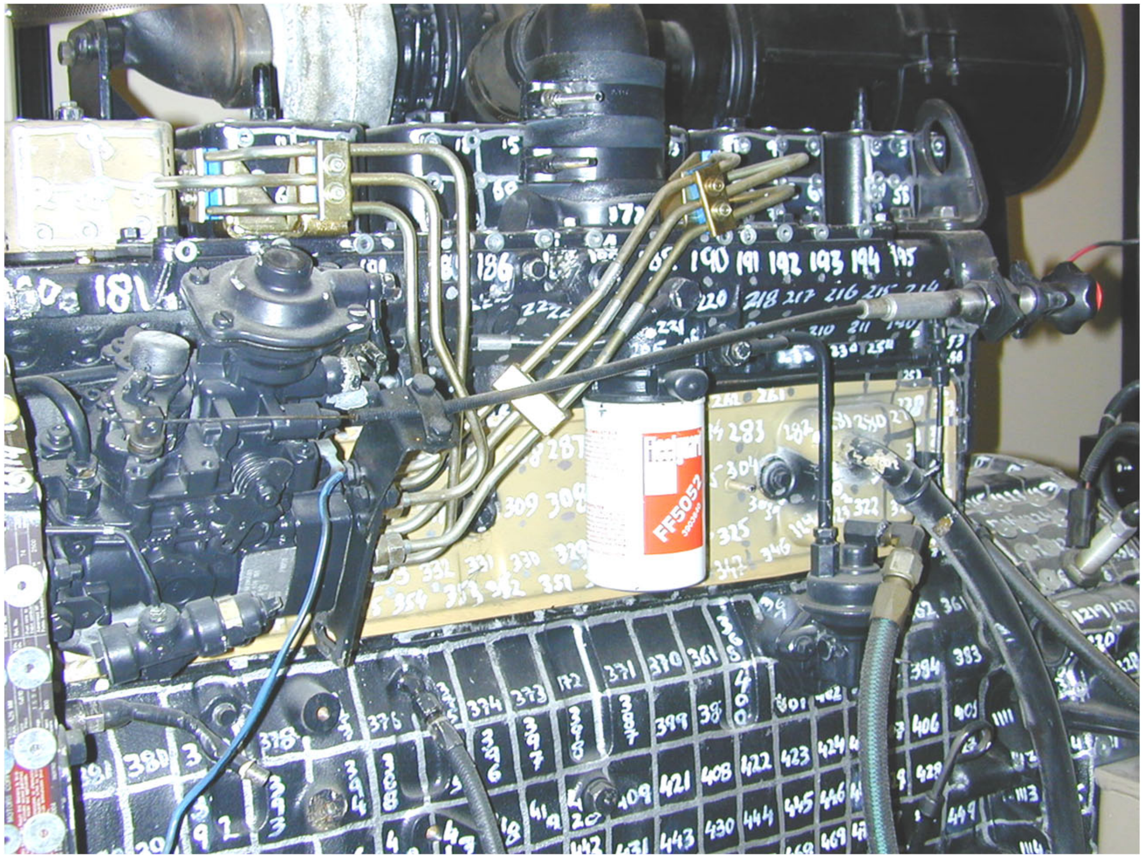
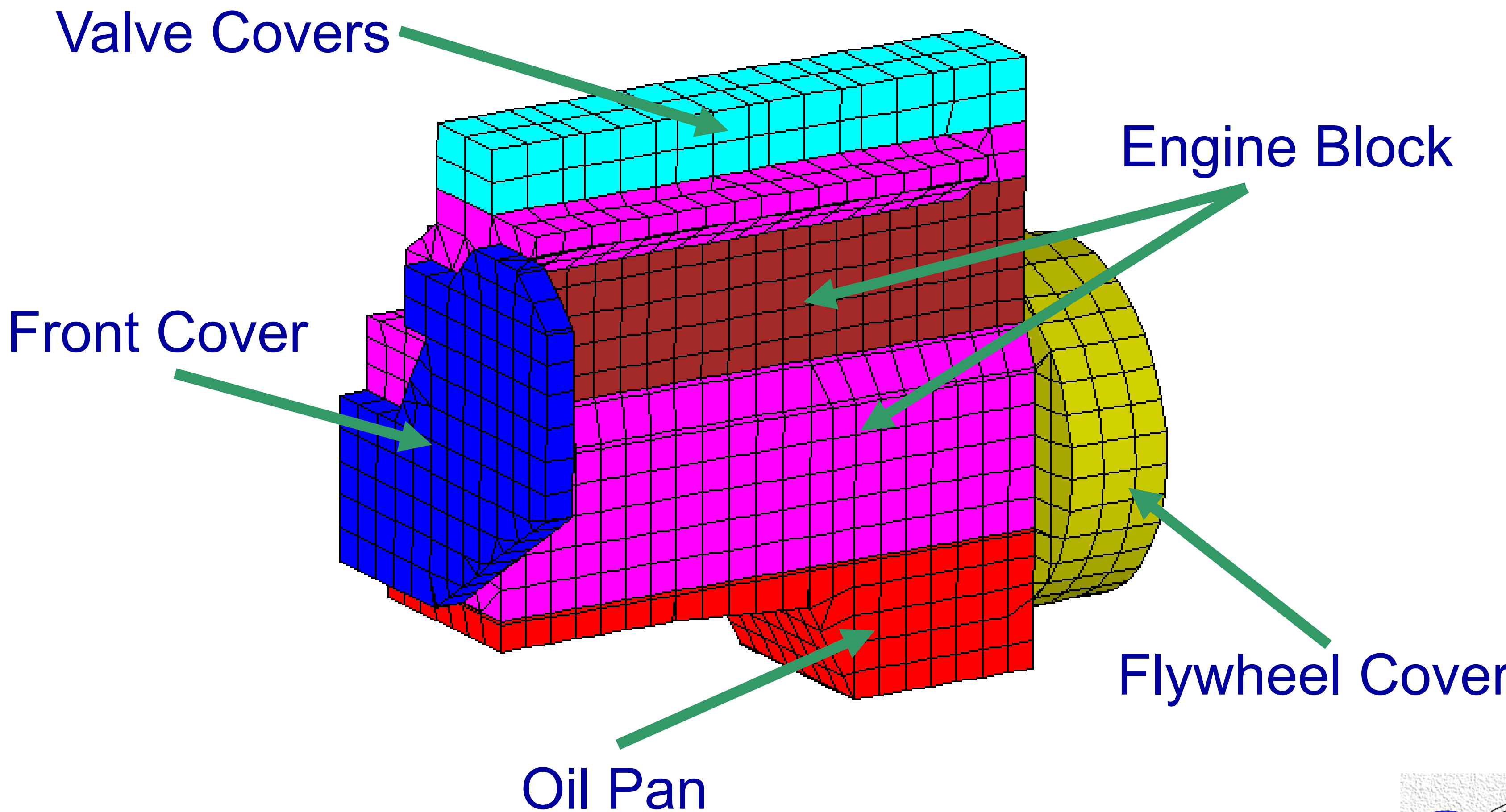
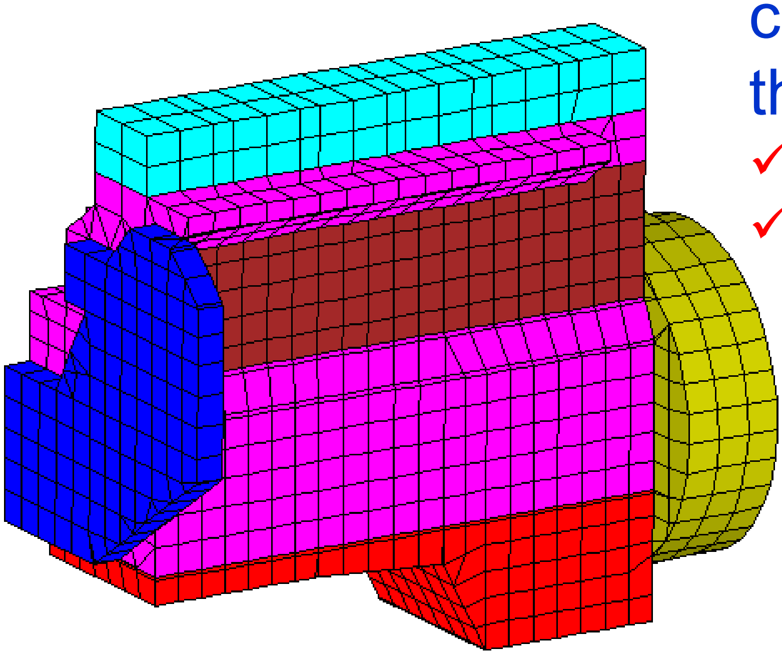
Engine Block



Engine Components

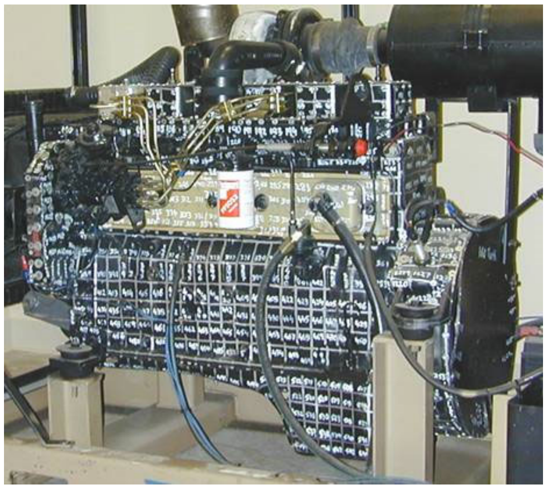


Contribution and Radiation Efficiency

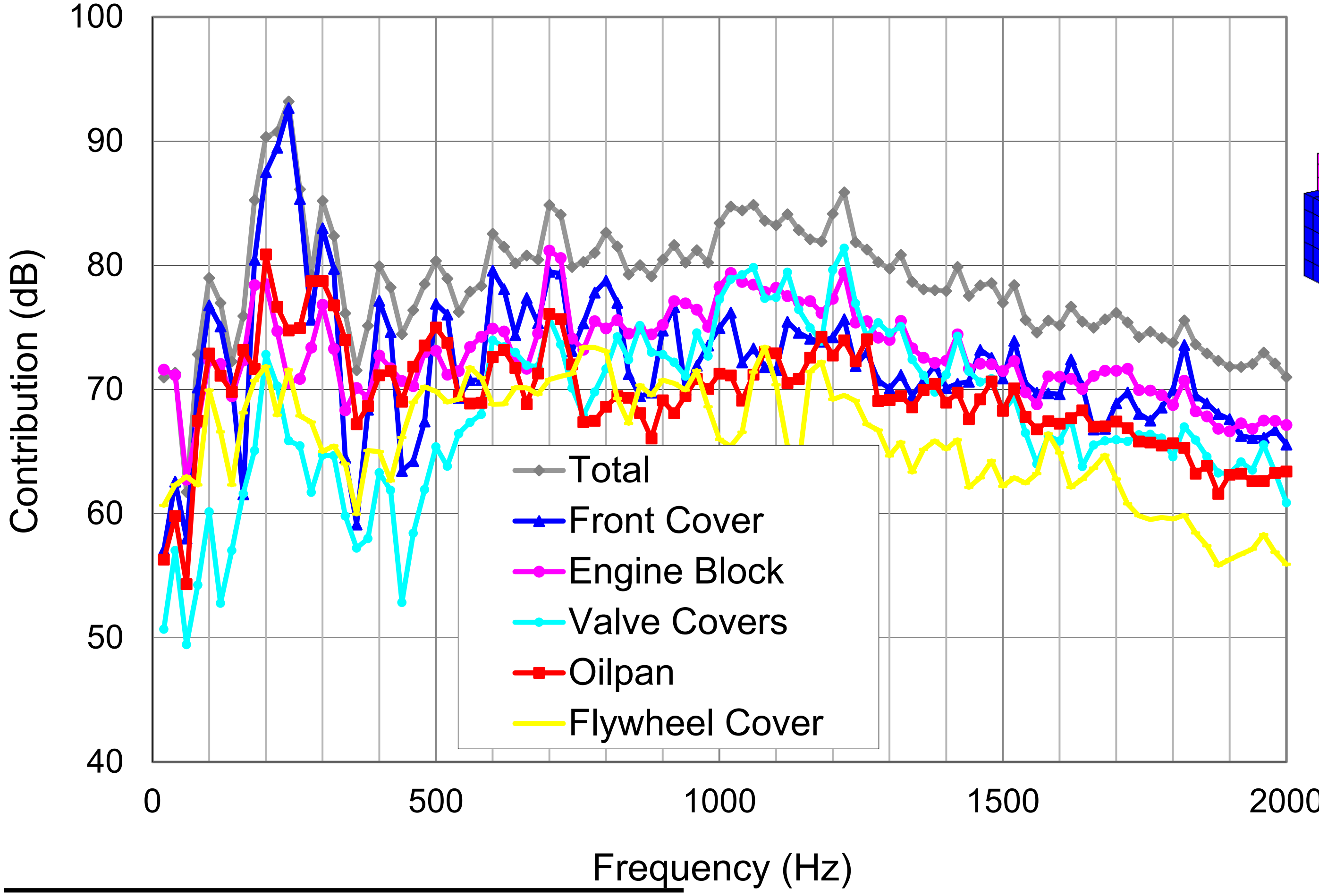


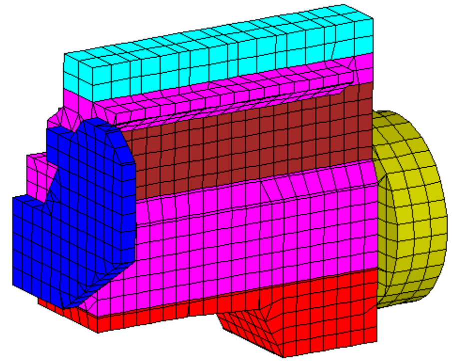
Make everything rigid except the component of interest and solve for the field point pressures

- ✓ Sound Power Contribution
- ✓ Radiation Efficiency

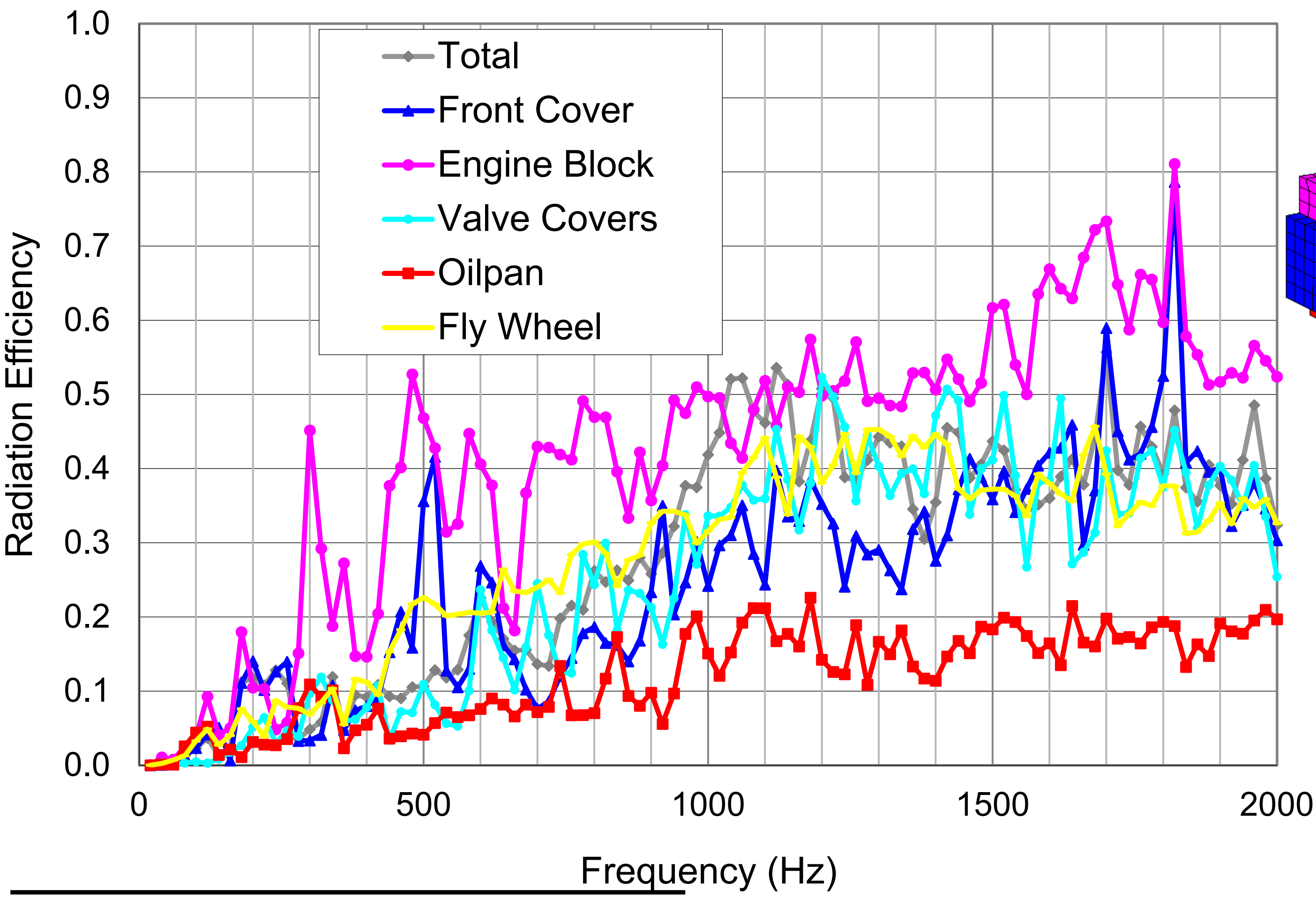


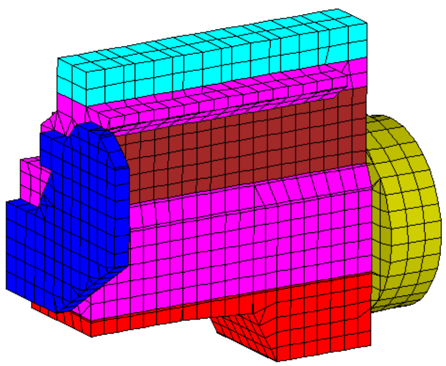
Sound Power Contribution



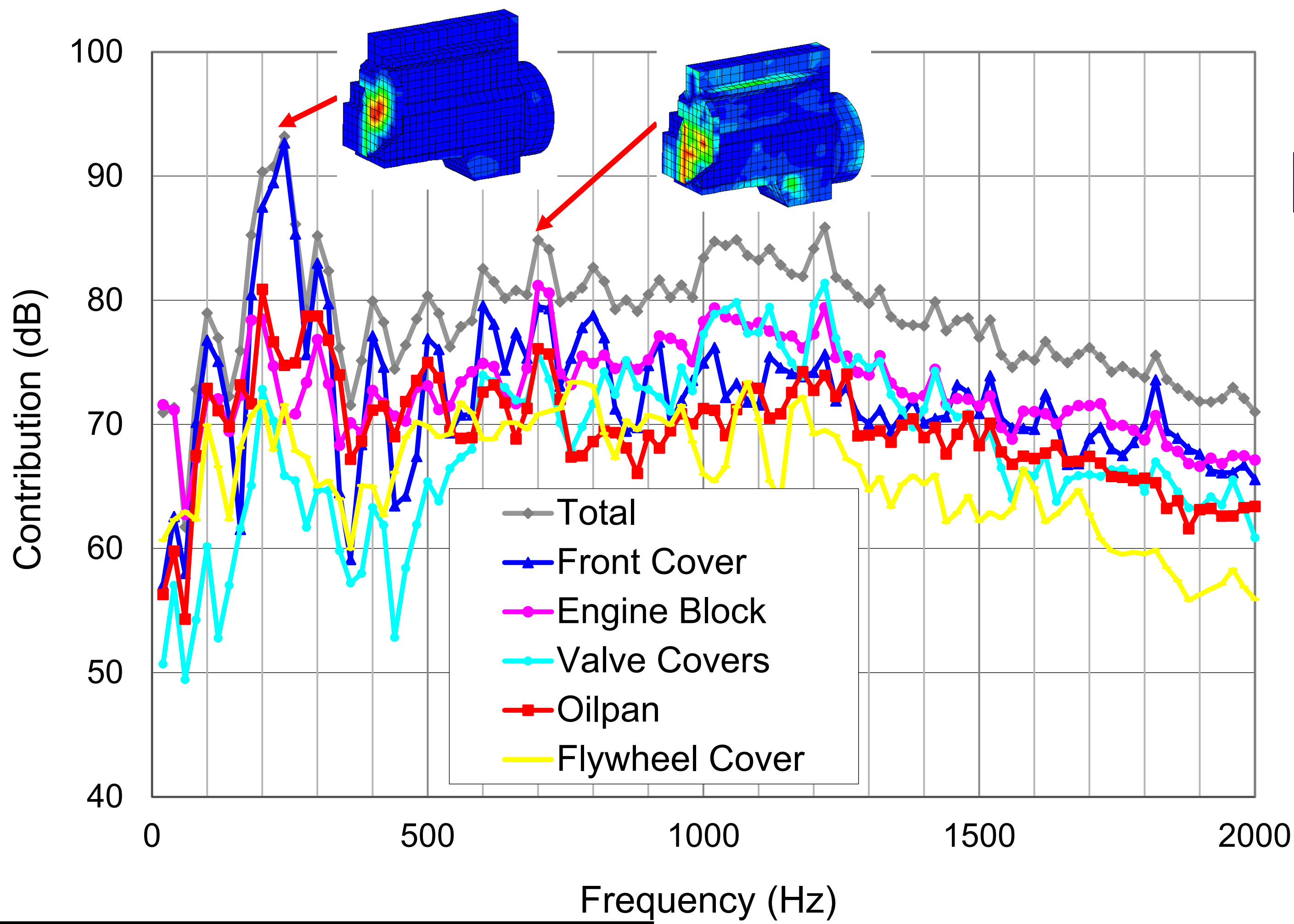


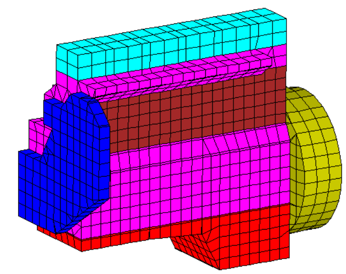
Radiation Efficiency





Results Interpretation





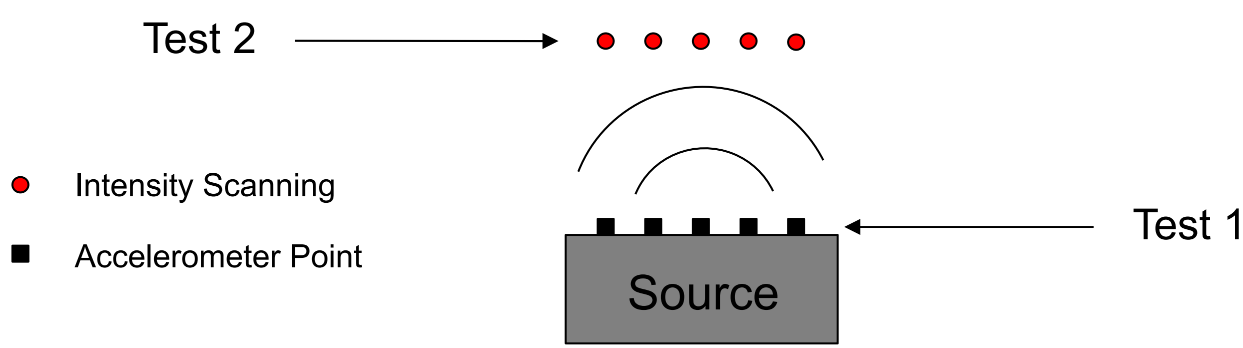
Overview

- Definition / Importance
- Example – Diesel Engine
- Measurement

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

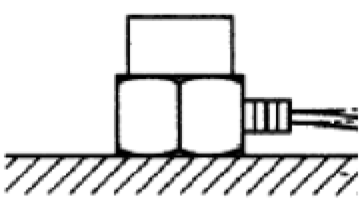
- Test 1 – Accelerometer Array for Surface Velocity
- Test 2 – Intensity Scan for Radiated Sound Power



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.

Microphone PU Probe

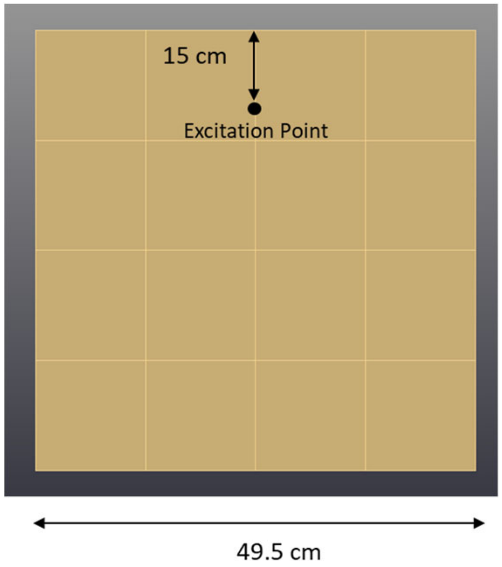
Microflown for measuring particle velocity and a microphone for measuring sound pressure.

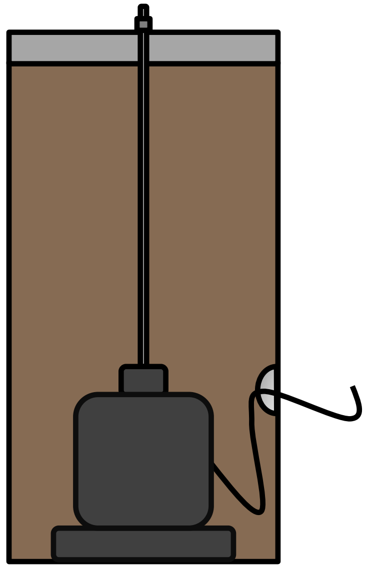
References

- H-E de Bree, P. Leussink, T. Korthorst, H. Jansen, T.S. Lammerink, amd M. Elwenspoek, “The µ-Flown: a Novel Device for Measuring Acoustic Flows”, Sensors and Actuators A: Physical, 54(1-3), 552-557 (1996).
- H-E de Bree, “The Microflown, a New Particle Velocity Sensor,” Sound and Vibration Magazine, 39(2), 8, (2005).
- The Microflown E-book, Online, 2009.

Test 1 Aluminum Plate

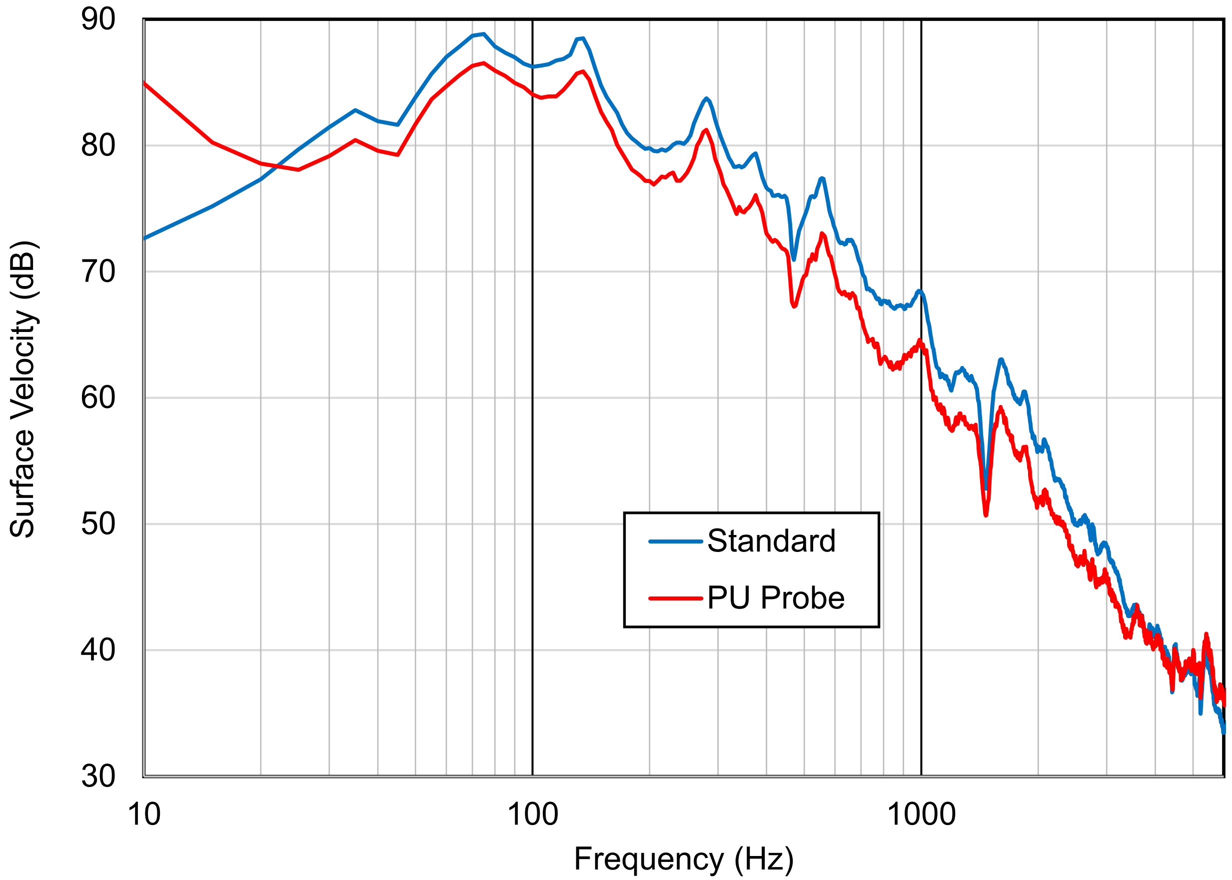
- Aluminum plate (3.175 mm thick)
- White noise from 0-6400 Hz



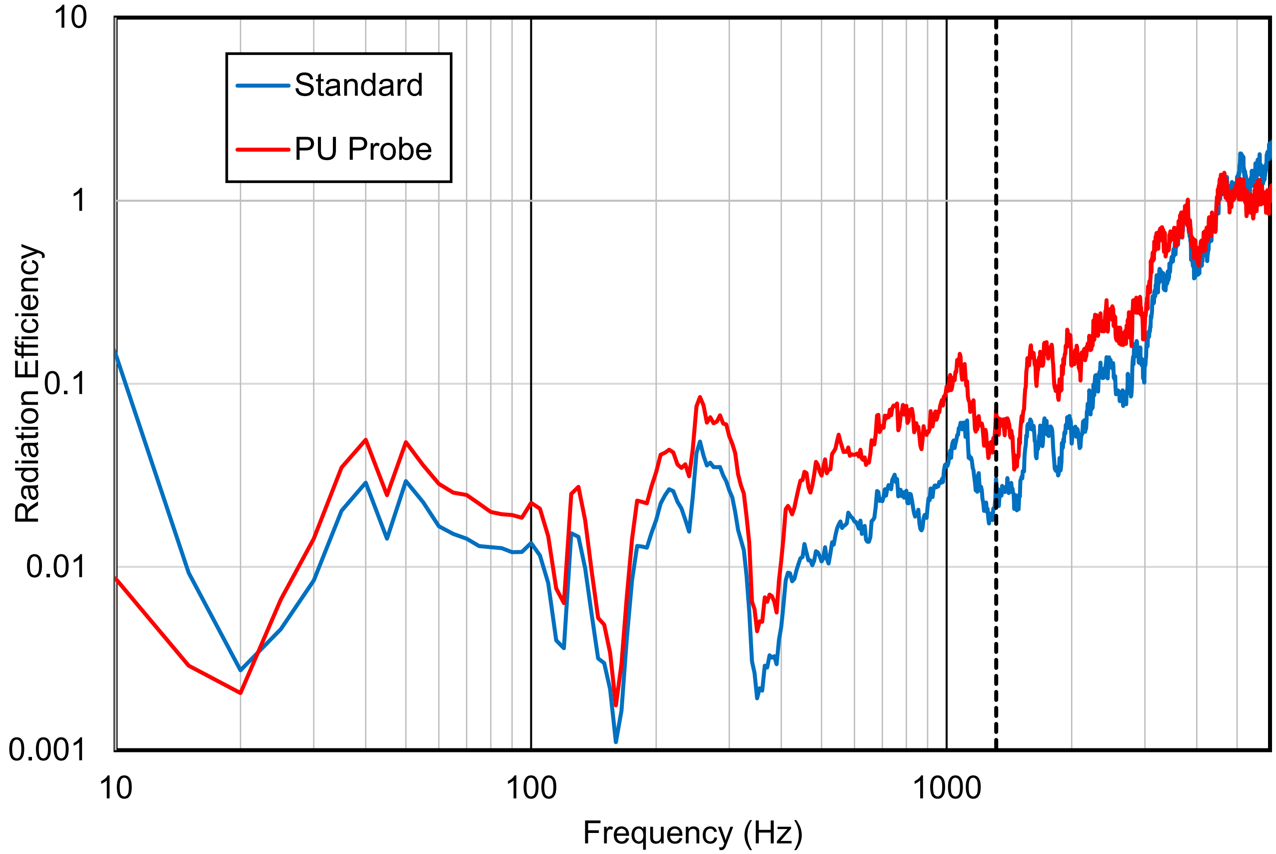


July 15, 2021

Test 1 Surface/Particle Velocity

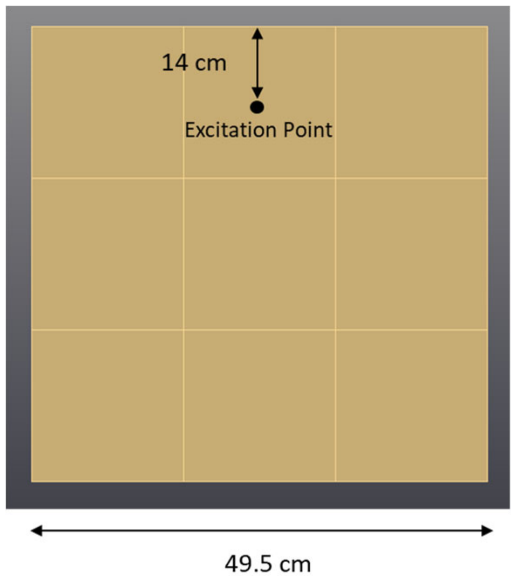


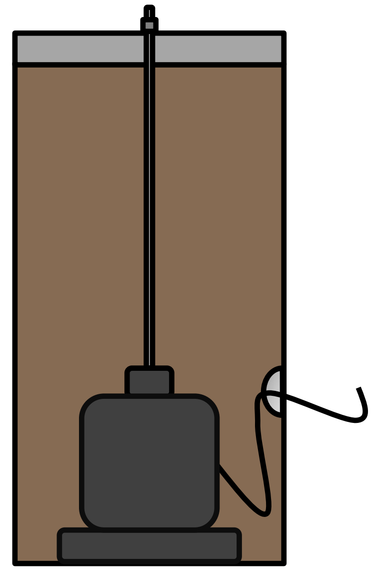
Test 1 Radiation Efficiency



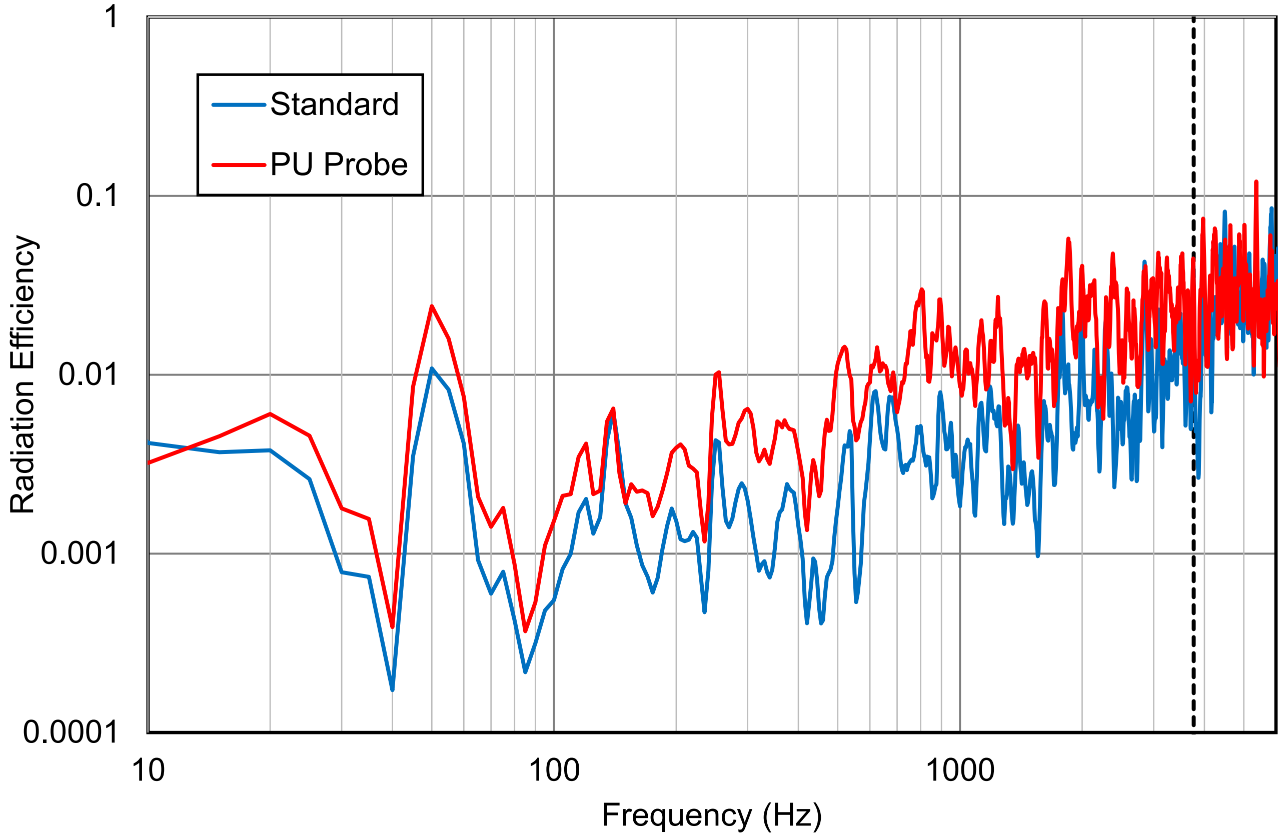
Test 2 Stainless Plate

- Stainless steel plate (1 mm thick)
- White noise from 0-6400 Hz



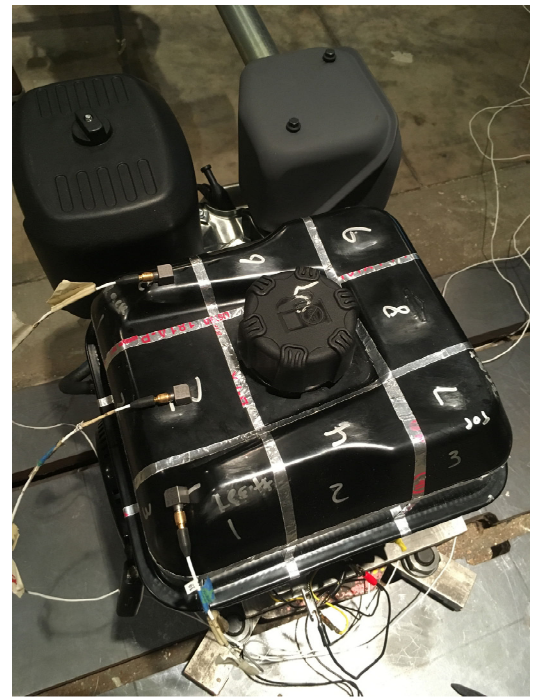


Test 2 Radiation Efficiency

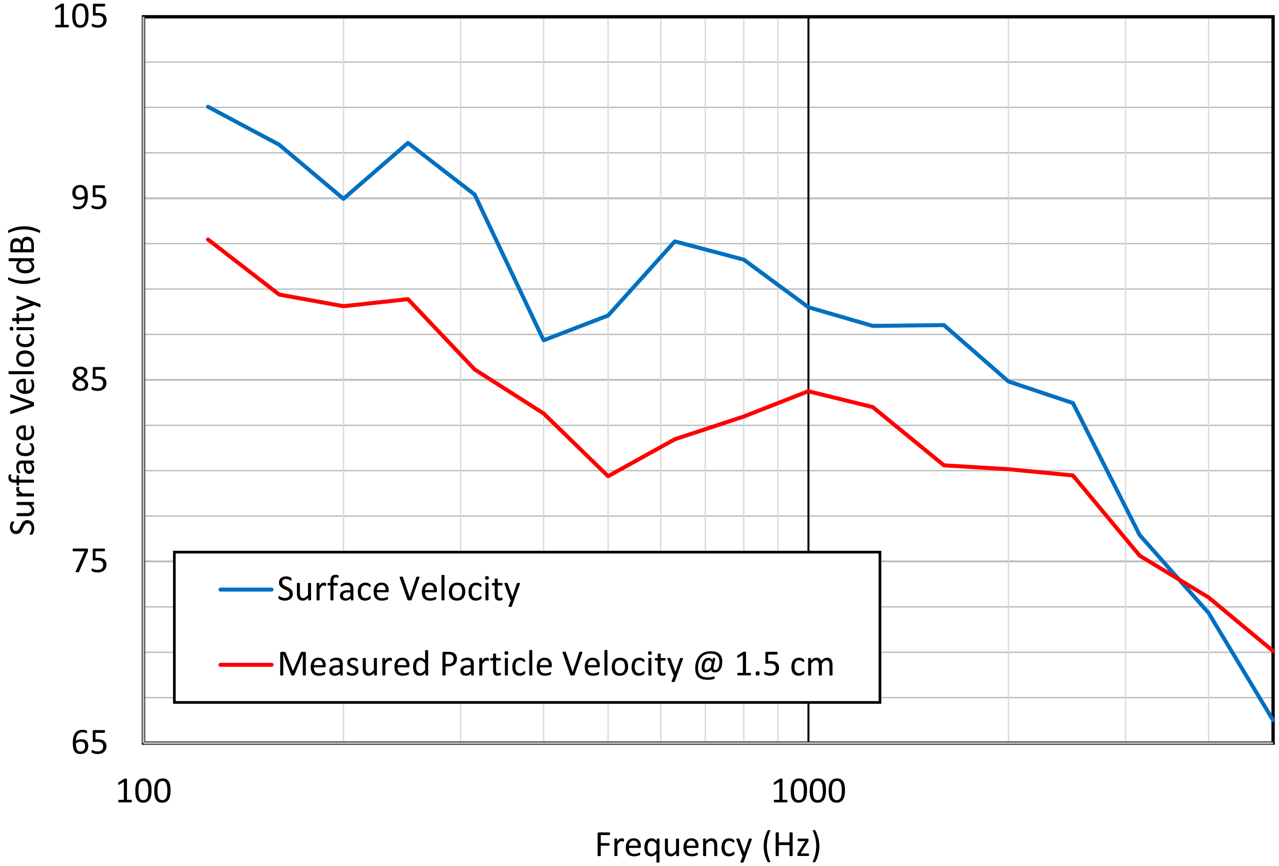


Test 3 Gas Tank

- Two shell metal composite gas tank.
- Excited by 420cc engine running at 2800 RPM.
- Only measured contributions coming from exposed surfaces due to probe limitations.



Test 3 Surface/Particle Velocity



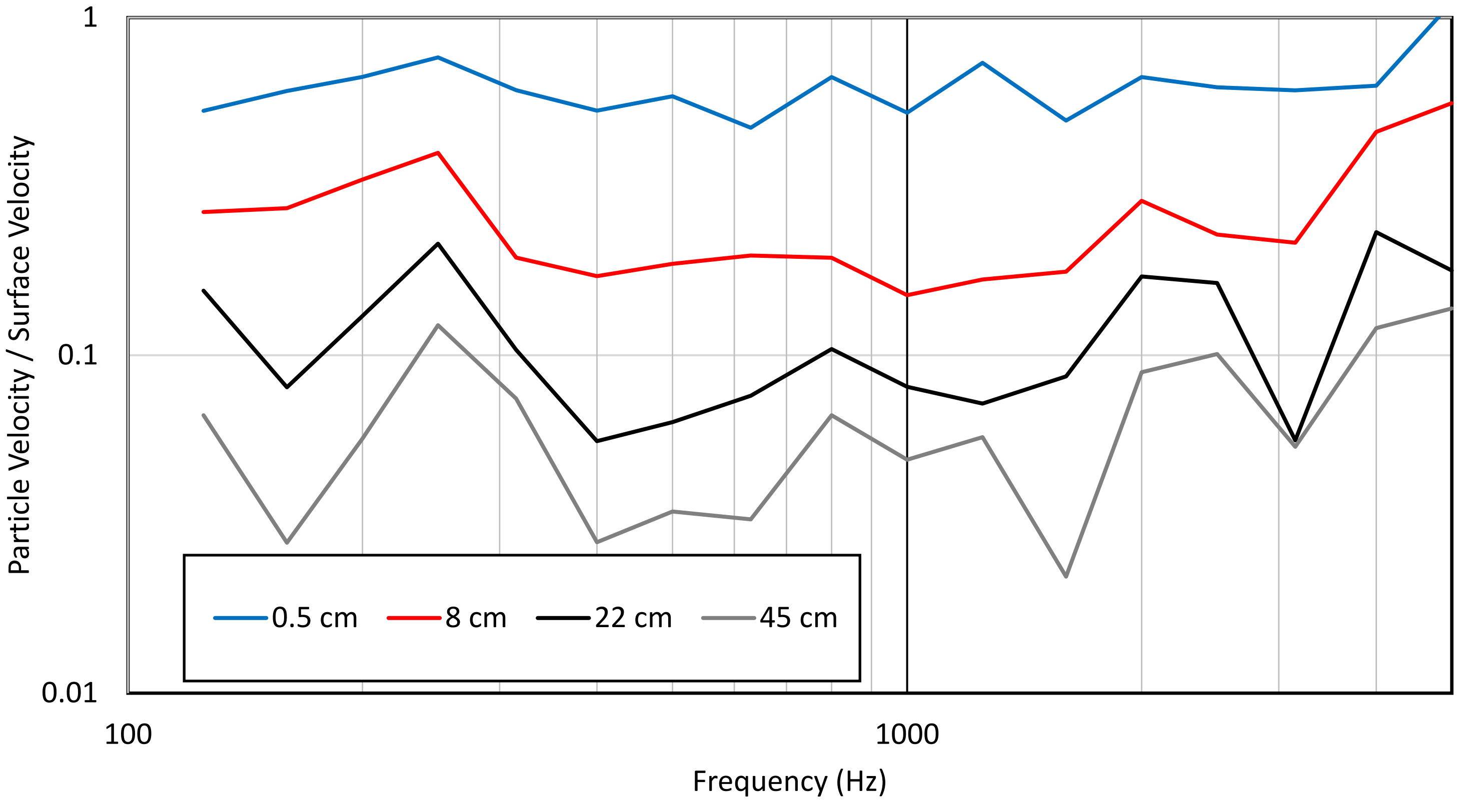
Some Observations

Particle velocity depends on the:

- Distance from the source
- Structure
- Frequency

Hence … No correction equation will be completely satisfactory.

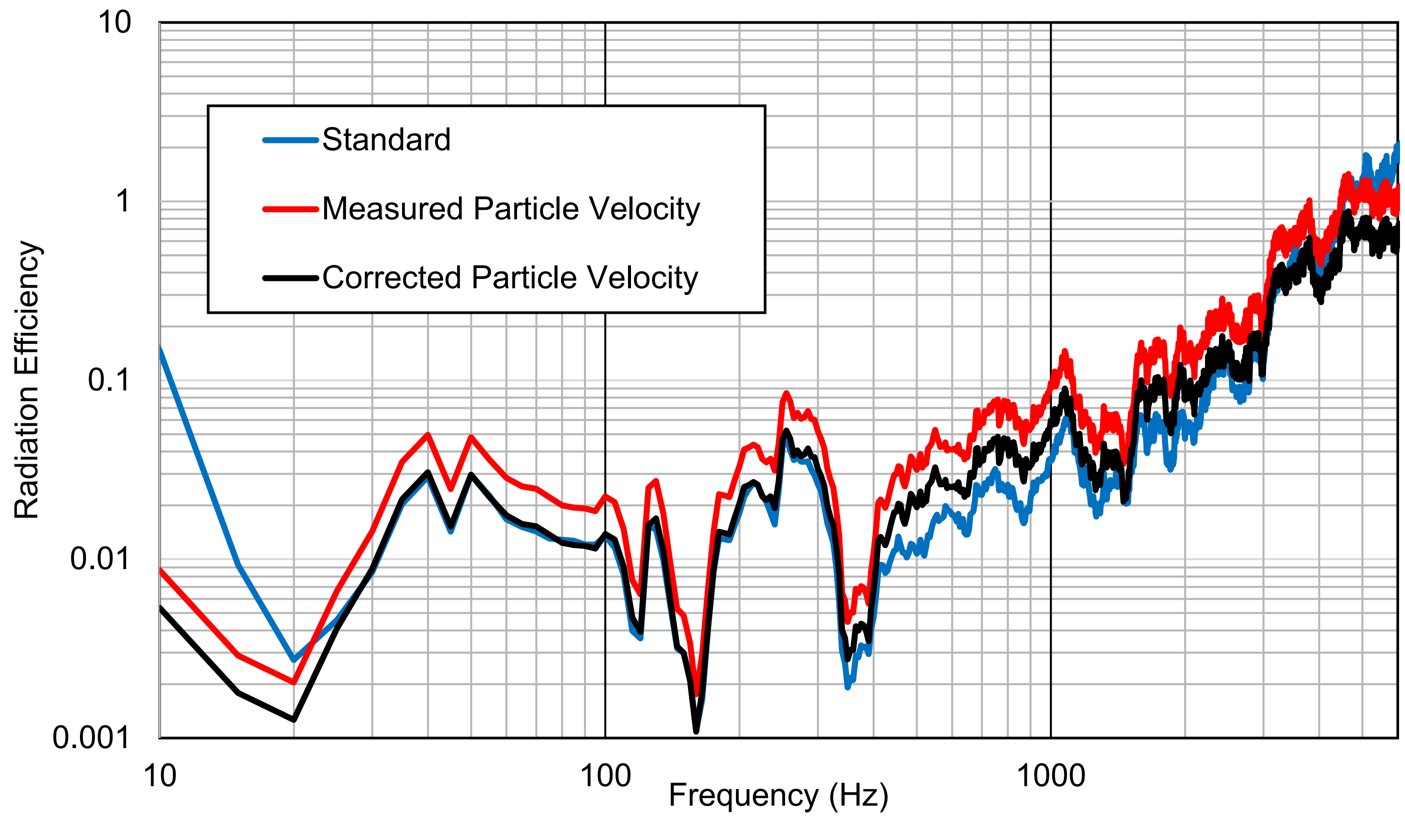
Particle Velocity Sensitivity Study



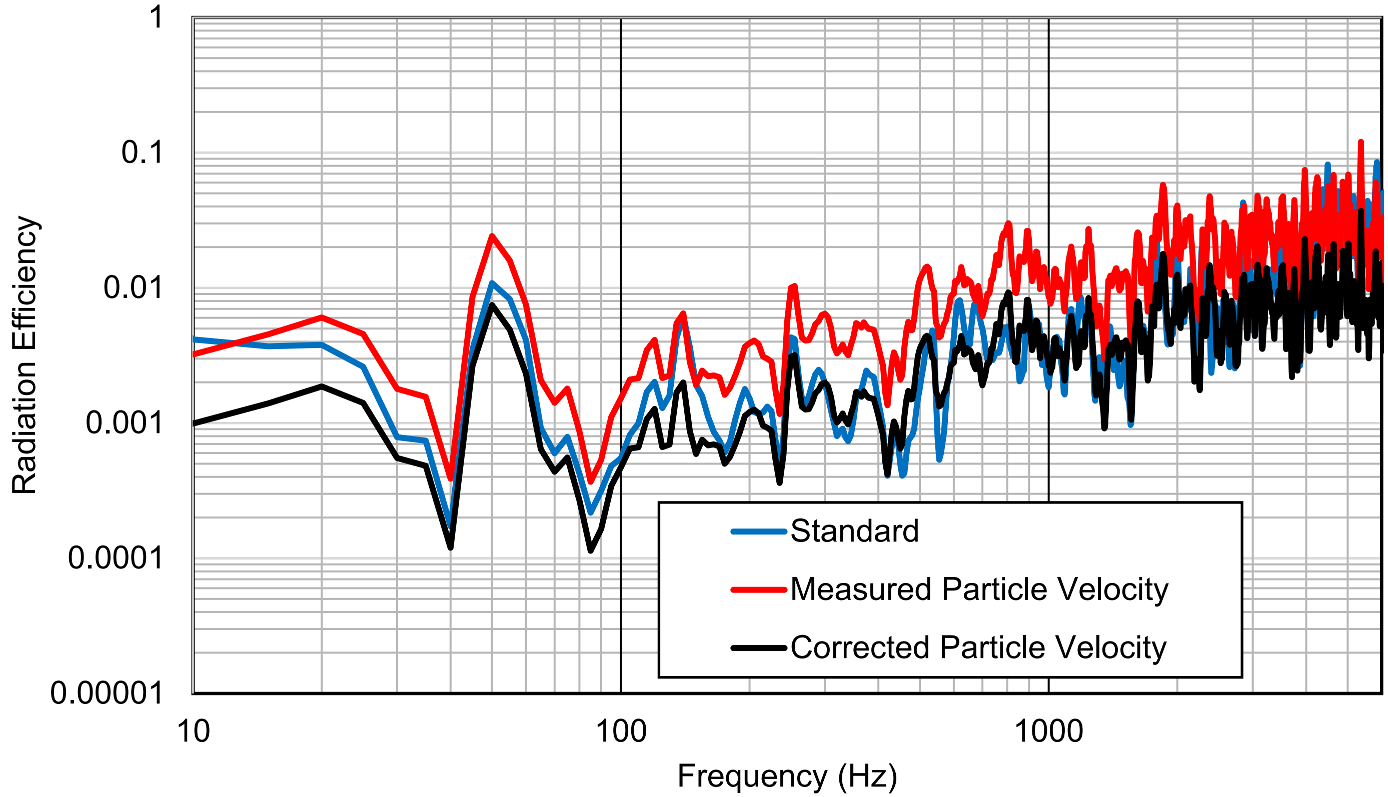
Correction Factor

- Taking the data from the sensitivity study we can “calibrate” the PU probe.
- This was done for the Aluminum plate test case and was applied for the stainless plate case and gas tank.
- At a distance away 0.5 cm, the scaling factor for the particle velocity was 1.8.
- This was applied to both plate test cases.

Test 1 Aluminum Plate



Test 2 Stainless Steel Plate

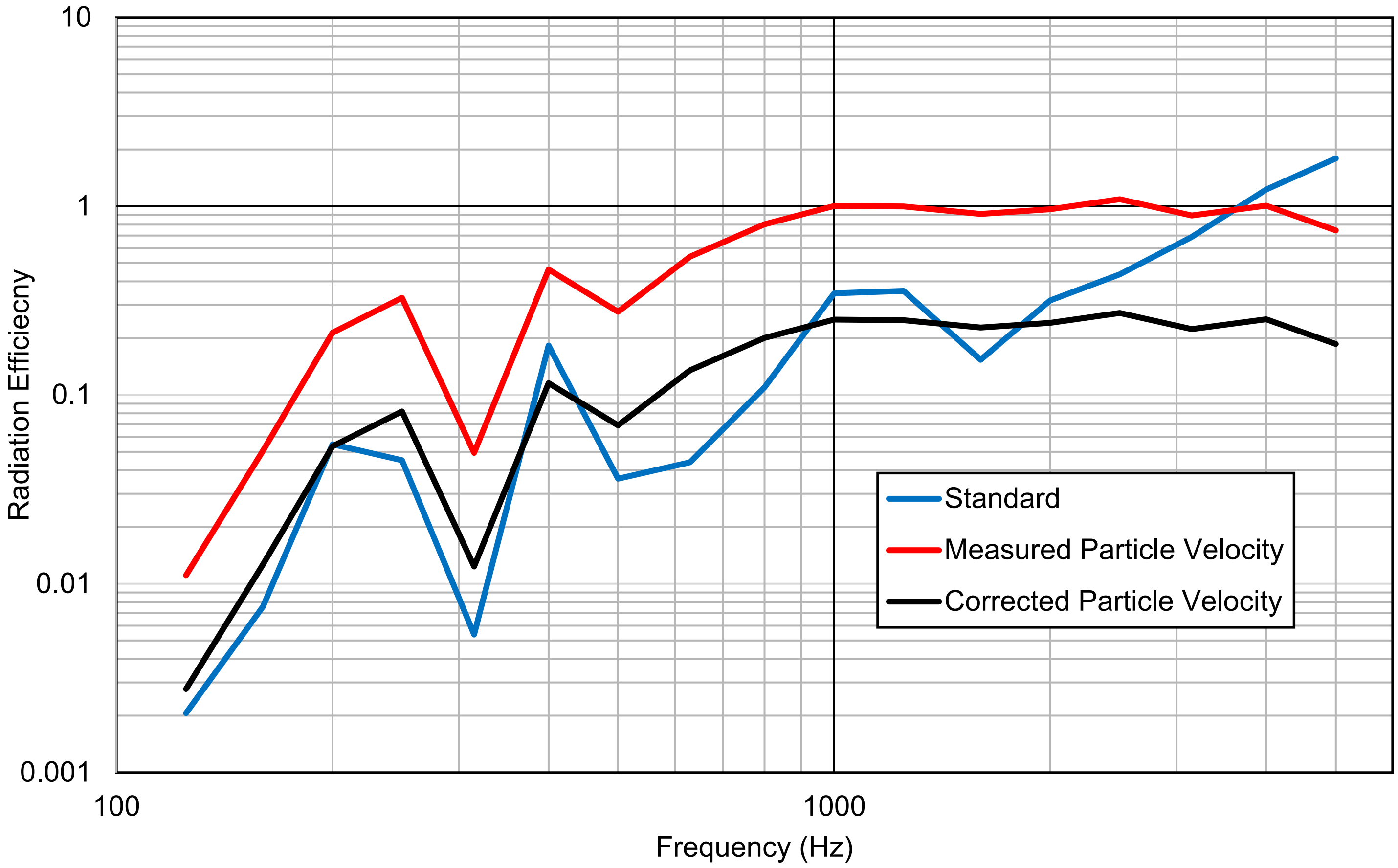


Correction Factor

- From the sensitivity study on the aluminum plate case, the results were extrapolated for the gas tank test at 1.5 cm.
- The correction factor used was 2.0 for the particle velocity.
- As the PU probe moves farther away from the source, the correction factor grows larger.

July 15, 2021

Test 3 Radiation Efficiency



Summary

- Radiation efficiency may be determined using a PU probe.
- Recommend calibrating the particle velocity measurement to the panel vibration with an accelerometer measurement at a similar distance away.

References

General Explanations

- D. A. Bies, C. H. Hansen, and C. Q. Howard, *Engineering Noise Control*, 5th Edition, CRC Press, Boca Raton, FL (2018).

Standard Measurement Procedure

- ISO/TS 7849-2, Acoustics — Determination of airborne sound power levels emitted by machinery using vibration measurement — Part 2: Engineering method including determination of the adequate radiation factor, International Organization for Standardization, Geneva, (2009).

UK Work

- S. C. Campbell, D. W. Herrin, B. Birschbach, and P. Crowley, "Measurement of Radiation Efficiency with a Combination Sound Pressure – Particle Velocity Sensor," Noise-Con 2019, San Diego, CA, August 26-28 (2019).