July 30, 2020

Back of the Envelope Methods for Assessing Noise and Vibration

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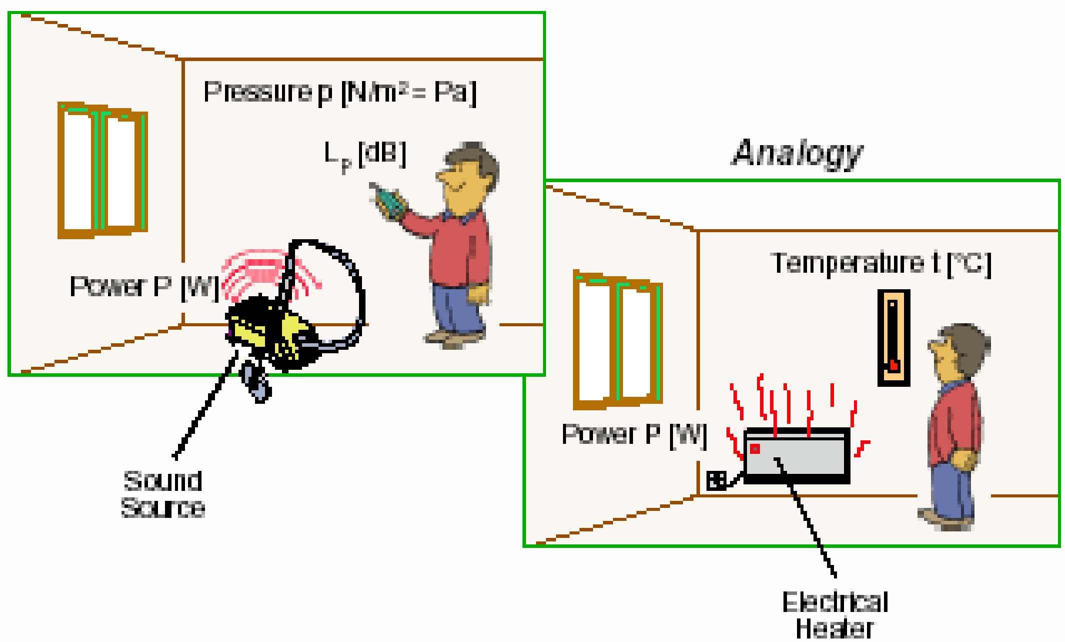
Overview

- Fundamentals
- Equations for Common Situations
- Examples

An Analogy



Like temperature, the sound pressure depends on the source power level AND the environment in which the source is placed.

Sound Pressure and Sound Power

$$W_S = IS = \left(\frac{p_{rms}^2}{\rho_o c}\right) S$$

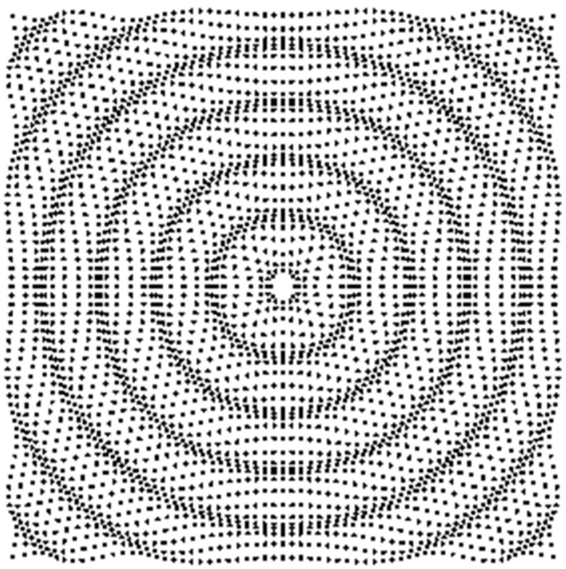
$$10\log_{10}\left(\frac{W_S}{W_{ref}}\right) = 10\log_{10}\left(\frac{p_{rms}^2}{\rho_o c W_{ref}}\right) + 10\log_{10}(S)$$

$$P_{ref} = 20 \times 10^{-6}\ \mathrm{Pa}$$

$$W_{ref} = 1.0 \times 10^{-12}\ \mathrm{W}$$

$$L_W \approx L_P + 10\log_{10}(S)$$

Sound Pressure and Sound Power



$$L_W \approx L_P + 10\log_{10}(S)$$

$$L_W \approx L_P + 10\log_{10}(4\pi r^2)$$

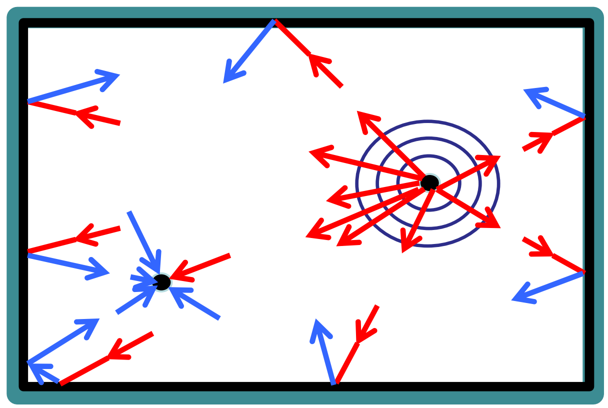
$$L_p \approx L_W + 10\log_{10}\left(\frac{1}{4\pi r^2}\right)$$

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

Room Acoustics Theory

Direct Field

Reverberant Field



$$L_p = L_W + 10\log\left(\frac{\Gamma}{4\pi r^2} + \frac{4}{R_r}\right)$$

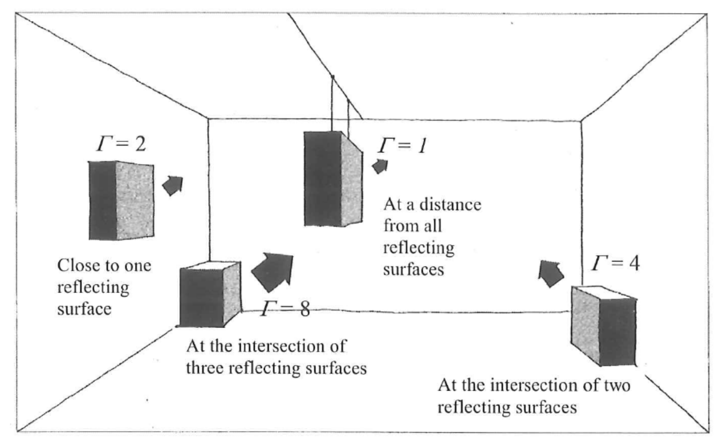
Direct Field

Reverberant Field

$$p_{ref} = 20 \times 10^{-6}\ \text{Pa}$$

$$W_{ref} = 1.0 \times 10^{-12}\ \text{W}$$

Finding Γ

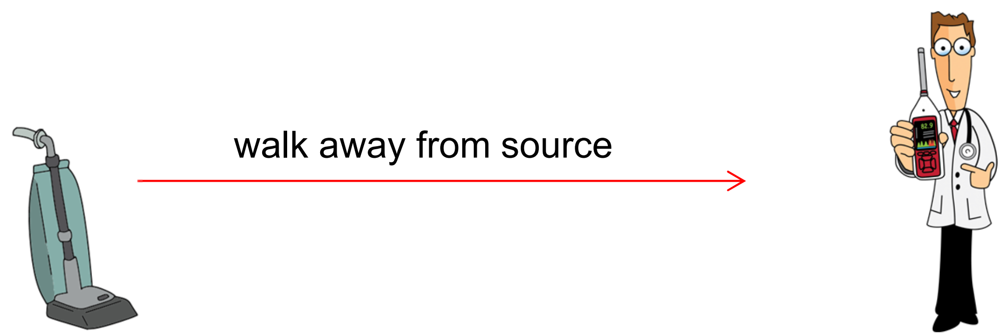


Room Acoustics Theory

Room Constant

$$R_r = \frac{\langle \alpha_d \rangle S}{1 - \langle \alpha_d \rangle}$$

$$L_p^{tot} = L_W^{dir} + 10\log\left(\cancel{\frac{\Gamma}{4\pi r^2}} + \frac{4}{R_r}\right)$$

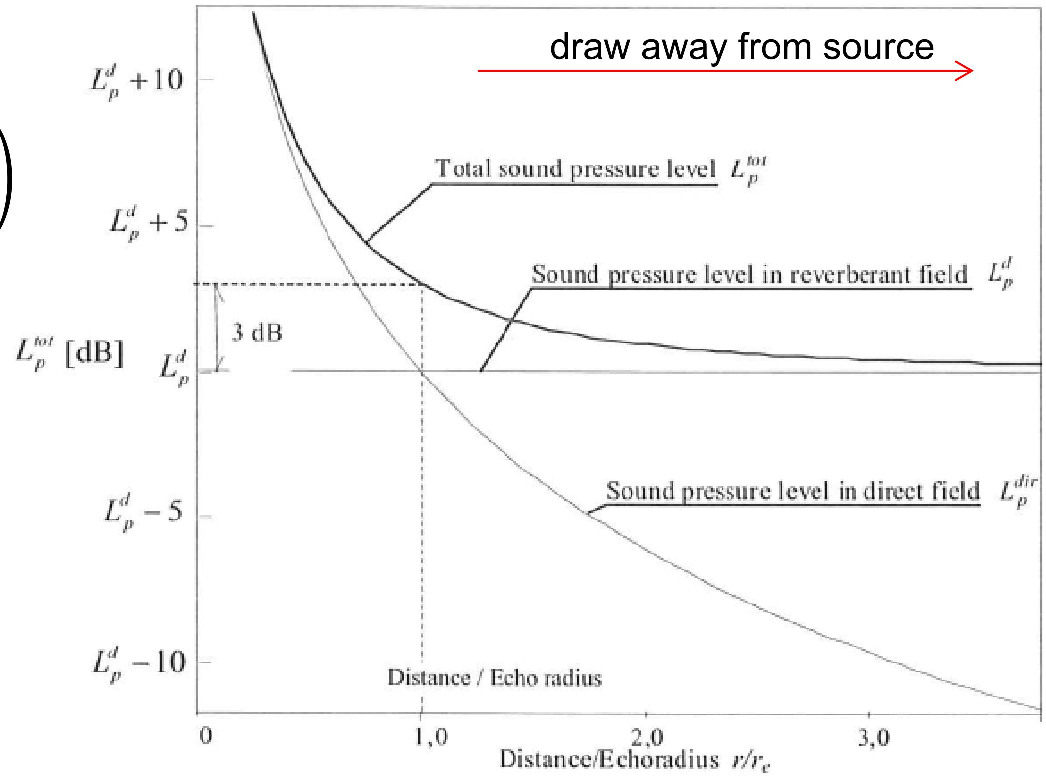


The Critical Distance

$$L_p = L_W + 10\log\left(\frac{\Gamma}{4\pi r^2} + \frac{4}{R_r}\right)$$

Critical Distance

$$r_e = \left(\frac{R_r \Gamma}{16\pi}\right)^{\frac{1}{2}}$$



Example

A noise source produces an average sound pressure level of 70 dB at a distance of 10 m from the source in a free field. The source is placed into a room with dimensions of 4 m x 5 m x 3 m. The interior walls are estimated to have an average absorption coefficient of 0.1. Estimate the sound pressure level in the room 2 m from the source. Is the sound absorption effective?

Free Field Source

$$L_p = L_W + 10\log\left(\frac{\Gamma}{4\pi r^2}\right)$$

$$L_W = L_p - 10\log\left(\frac{\Gamma}{4\pi r^2}\right)$$

$$L_W = 70 - 10\log\left(\frac{1}{4\pi(10)^2}\right)\ \text{dB}$$

$$L_W = 101\ \text{dB}$$

Source in Room

$$L_p^{tot} = L_W^{dir} + 10\log\left(\frac{\Gamma}{4\pi r^2} + \frac{4(1-\langle\alpha_d\rangle)}{\langle\alpha_d\rangle S}\right)$$

$$L_p^{tot} = 101 + 10\log\left(\frac{1}{4\pi(2)^2} + \frac{4(1-0.1)}{(0.1)(94)}\right)$$

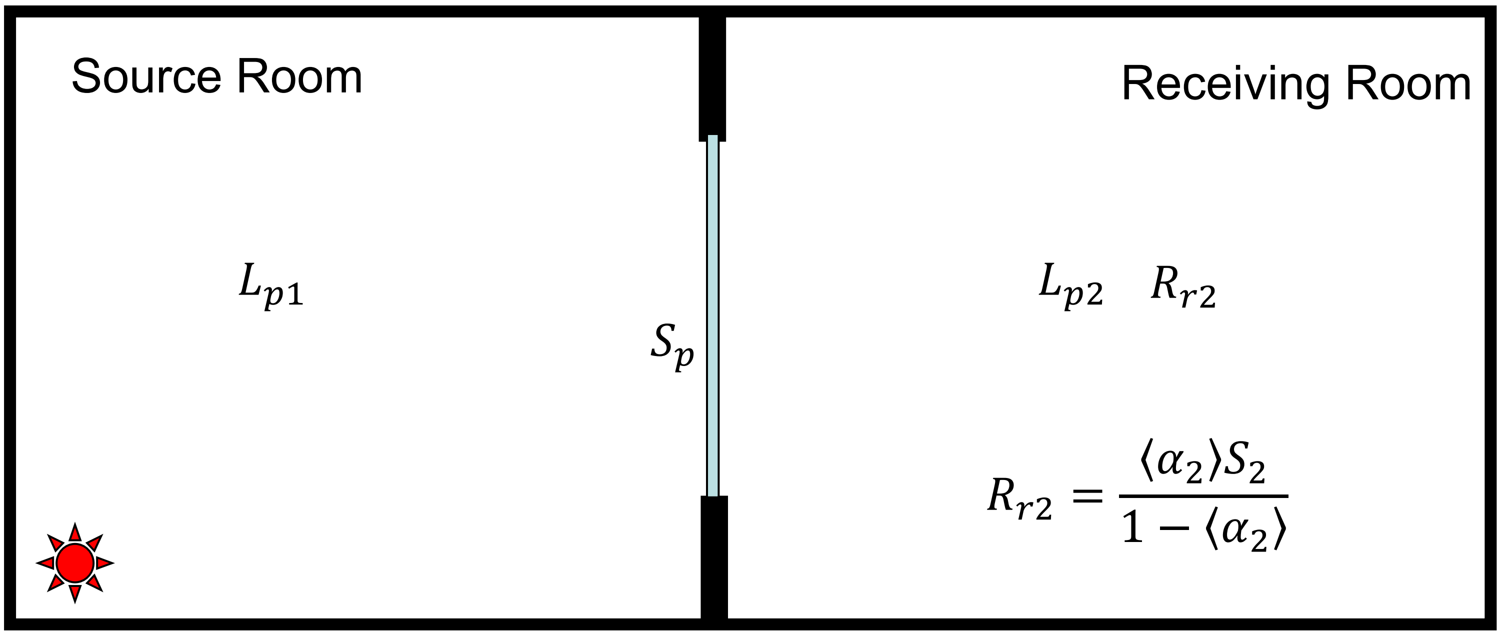
$$L_p^{tot} = 97.1\ \text{dB}$$

Critical Distance

$$r_e = \left(\frac{R_r\Gamma}{16\pi}\right)^{1/2}$$

$$r_e = 0.46\ \text{m}$$

Sound Transmission Between Rooms



$$L_{p1} - L_{p2} = SI + 10\log\left(\frac{R_{r2}}{S_p}\right)$$

Transmission Loss of a Panel

$$\tau = \frac{2\rho c S}{\omega m} \qquad \omega = 2\pi f$$

$$TL = 20\log_{10}\left(\frac{1}{\tau}\right) = 20\log_{10}\left(\frac{m\pi}{\rho c S} f\right)$$

$$TL = 20\log_{10}\left(\frac{m}{S} f\right) - 20\log_{10}\left(\frac{\rho c}{\pi}\right)$$

$$\rho_s = \frac{m}{S}$$ (panel surface density = bulk density × thickness)

$$TL = 20\log_{10}(\rho_s f) - 42\ \mathrm{dB}$$ for air, SI units

Transmission Loss of a Composite Panel

For each part of the panel

$$\tau_i = \frac{1}{1 + \left(\frac{\omega m_i}{2\rho_0 c S_i}\right)^2} \approx \left(\frac{2\rho c S_i}{\omega m_i}\right)^2 = \left(\frac{\rho c}{\pi f \rho_{si}}\right)^2$$

For composite panels

$$\tau_{total} = \frac{\sum \tau_i S_i}{S_{total}}$$

Transmission loss

$$TL_{total} = 10 \log_{10} \frac{1}{\tau_{total}}$$

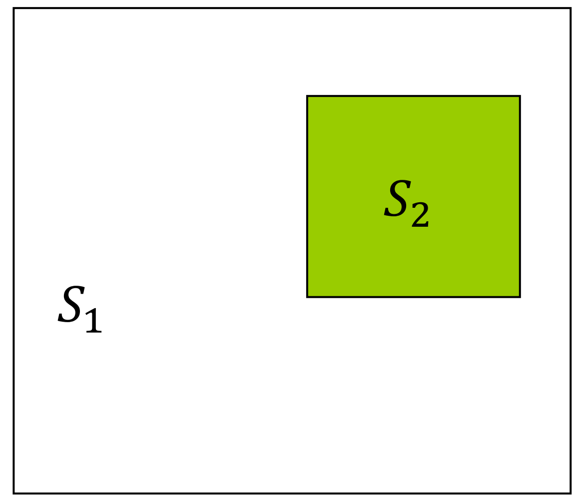
Transmission Loss of a Composite Panel

$$TL_{total} = 10\log_{10}\frac{1}{\tau_{total}}$$

$$\tau_{total} = \frac{1}{S_{total}}\sum_{n=1}^{N}\tau_n S_n \qquad S_{total} = \sum_{n=1}^{N} S_n$$

n	S_n	R_d	τ_n
1	2	20	0.01
2	2	10	0.1

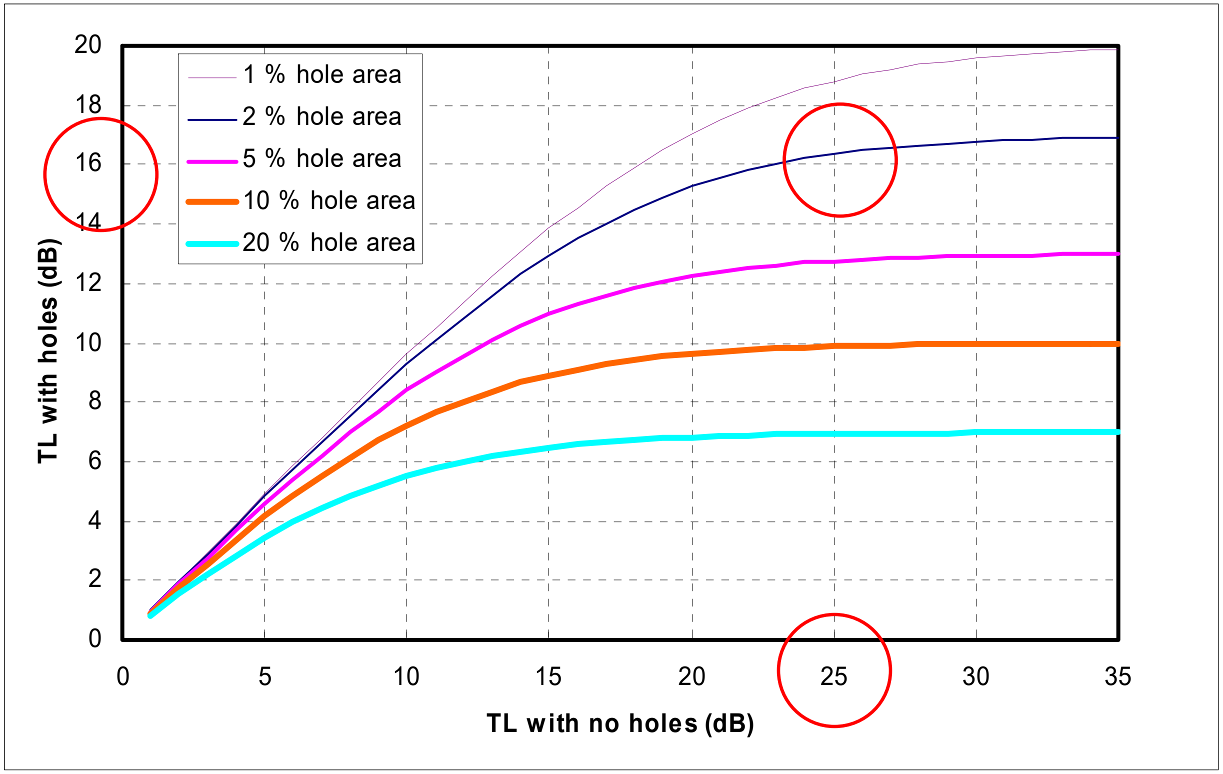
$$\tau = \frac{1}{4}(0.01\cdot 2 + 0.1\cdot 2) = 0.055$$



$$TL = 10\log_{10}\frac{1}{0.055} = 12.6\text{ dB}$$

Transmission Loss of a Composite Panel

Assume $\tau = 1$ for openings.



Oblique Incident Sound Transmission

Diffusive sound field: plane waves of the same average intensity travelling with equal probability in all directions.

$$\tau = \tau(\varphi) \qquad \qquad \tau = \frac{\int_0^{\varphi_{lim}} \tau(\varphi) \cos\varphi \sin\varphi \, d\varphi}{\int_0^{\varphi_{lim}} \cos\varphi \sin\varphi \, d\varphi}$$

For random incidence $\varphi_{lim} = 90°$

$$TL_{random} = TL_{\perp} - 10 \log_{10}(0.23 TL_{\perp})$$

For field incidence (better agreement with measurement) $\varphi_{lim} = 78°$

$$TL_{field} = TL_{\perp} - 5 \text{ dB}$$

Application Acoustic Enclosure

No Enclosure

$$I_{base} = \frac{W}{S_2 \alpha_2}$$

Intensity inside enclosure

$$I_{enc} = \frac{W}{S_1 \alpha_1 + S_1 \tau_1}$$

Intensity for enclosed source

$$I_{tr} = S_1 \tau_1 \left(\frac{W}{S_1 \alpha_1 + S_1 \tau_1} \right) \left(\frac{1}{S_2 \alpha_2} \right)$$

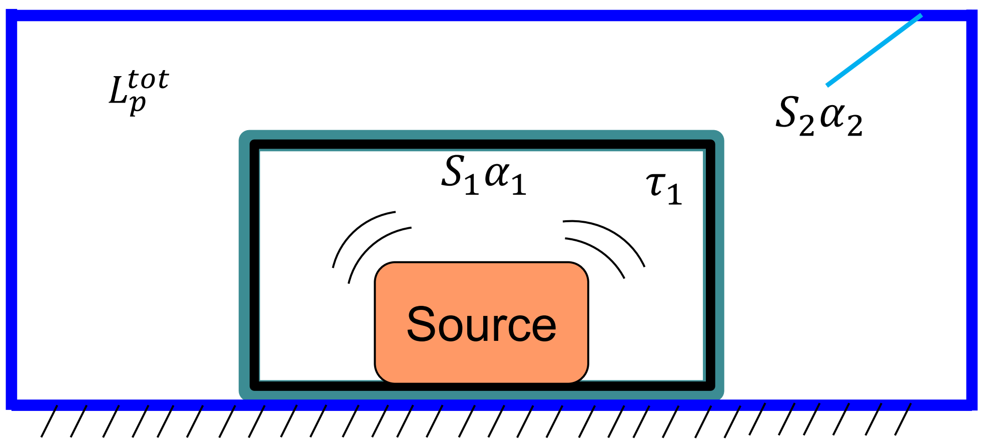
Enclosure Insertion Loss

$$TL = 10 \log_{10} \left(\frac{1}{\tau_1} \right)$$

$$IL = TL + 10 \log_{10}(\langle \alpha_1 \rangle + \langle \tau_1 \rangle)$$

$\langle \alpha \rangle >> \langle \tau \rangle$ → Typical

$$IL = TL + 10 \log_{10}(\langle \alpha_1 \rangle)$$



If $\alpha_1 = 0$

$$IL = TL + 10 \log_{10}(\langle \tau_1 \rangle) = TL - TL = 0$$

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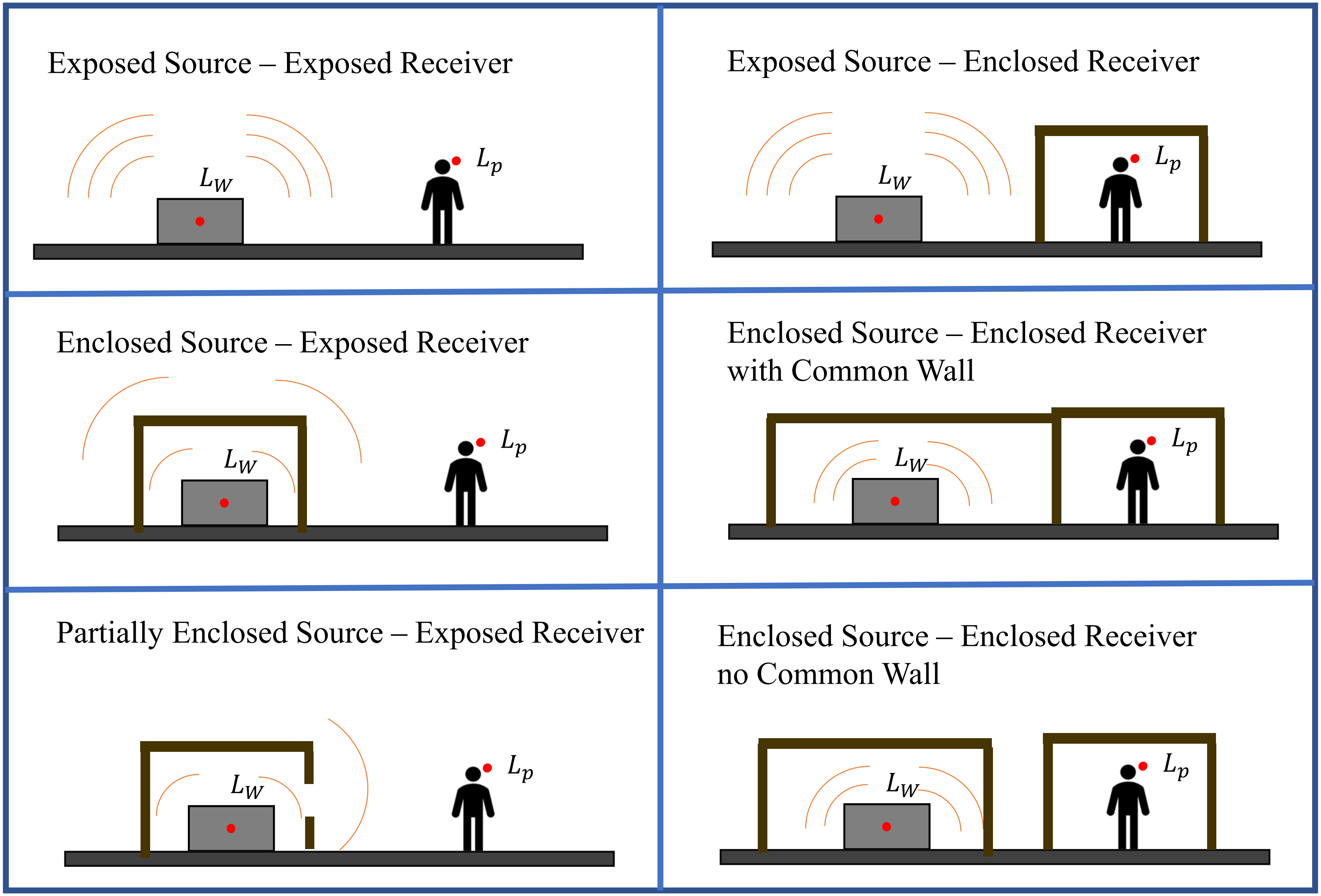
Spreadsheet Model Assumptions

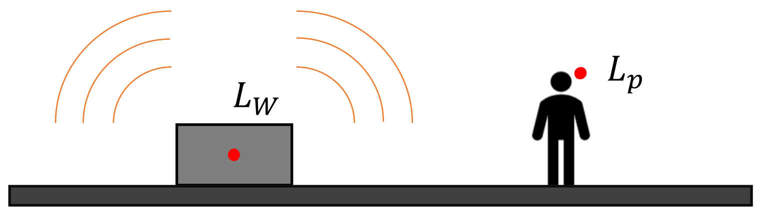
- Sound sources are incoherent, and the acoustic signals are wide band. Sound sources distributed at distances greater than $\lambda/6$ may be considered incoherent where λ is the acoustic wavelength.
- Sound fields in closed spaces are quasi-diffuse. As an approximation, the sound field in a closed space may be considered diffuse at frequencies above that of the 10^{th} acoustic mode.
- Sound pressure at any specific point is determined by the energy summation principle.
- Resonance phenomena are ignored as a rule.
- Sources generate sound fields which are idealized as spherical, cylindrical, or plane wave.
- Sources in closed spaces are assumed to be omni-directional.
- Closed spaces are characterized by an average coefficient of sound absorption.
- The ratio of the maximum to the minimum linear dimensions of acoustic spaces generally should not exceed 5. Other simplified models should be considered in that case.


Exposed Source – Exposed Receiver
L_W
L_p
Exposed Source – Enclosed Receiver
L_W
L_p
Enclosed Source – Exposed Receiver
L_W
L_p
Enclosed Source – Enclosed Receiver with Common Wall
L_W
L_p
Partially Enclosed Source – Exposed Receiver
L_W
L_p
Enclosed Source – Enclosed Receiver no Common Wall
L_W
L_p

Exposed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma\chi}{4\pi r^2}\right) + DI - \beta$$

Direct Field



Exposed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma\chi}{4\pi r^2}\right) + DI - \beta$$

L_p	Sound pressure level at receiver
L_W	Sound power of source
r	Distance from source to receiver
Γ	Symmetry planes
χ	Near field effect (can be ignored for small sources)
DI	Directivity Index
β	Location of Source

Exposed Source – Exposed Receiver

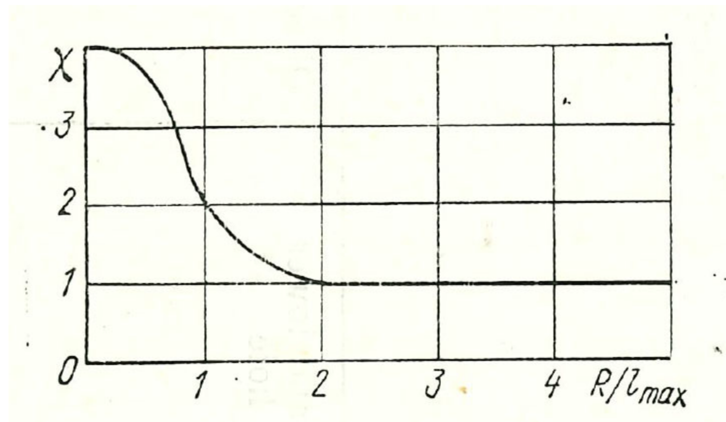
$$L_p = L_W + 10\log\left(\frac{\Gamma\chi}{4\pi r^2}\right) + DI - \beta$$

Direct Field

Near Field Adjustment

$$\chi = 2.5 + 1.5\cos\left(\frac{\pi}{2}\frac{r}{l_{max}}\right) \quad \text{for} \quad \frac{r}{l_{max}} < 2$$

$$\chi = 1 \quad \text{for} \quad \frac{r}{l_{max}} > 2$$



r distance from the source

l_{max} maximum linear dimension of source

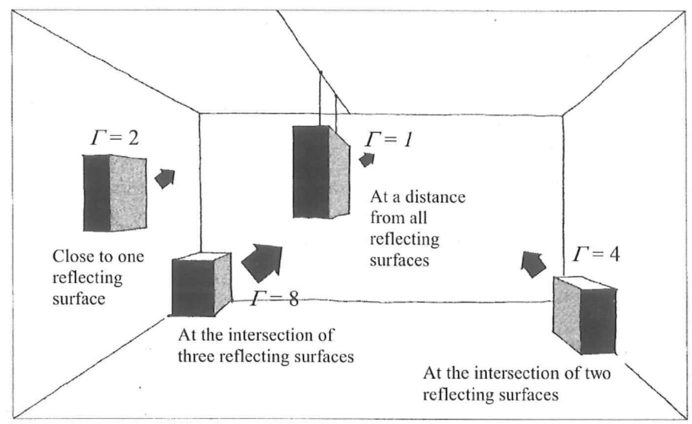
Exposed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma\chi}{4\pi r^2}\right) + DI - \beta$$

Direct Field

Symmetry Surfaces

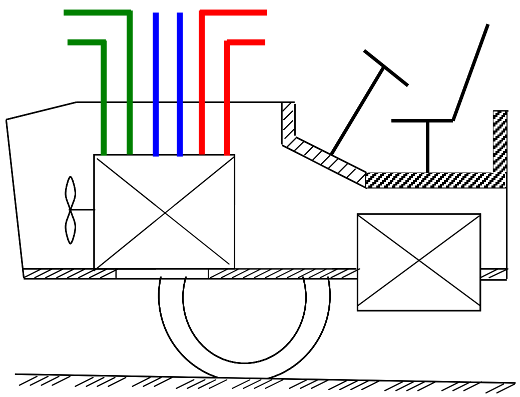
$\Gamma = 1$	Free Field
$\Gamma = 2$	1 Symmetry Surface
$\Gamma = 4$	2 Symmetry Surfaces
$\Gamma = 8$	3 Symmetry Surfaces



Exposed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma\chi}{4\pi r^2}\right) + DI - \beta$$

Directivity Index



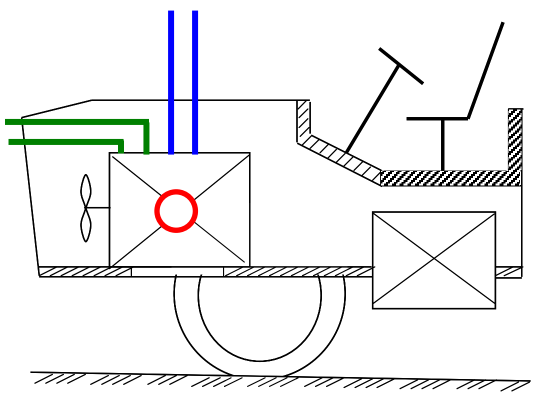
Directivity Index

1.	Upwards	$DI = 0$
2.	Towards Operator Loc.	$DI = 4$ dB
3.	Opposite Operator Loc.	$DI = -4$ dB

Exposed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma\chi}{4\pi r^2}\right) + DI - \beta$$

Source Shielding



Source Shielding

1. No Barrier $\beta = 0$
2. Partially Shielded $\beta = 5\ \mathrm{dB}$
3. Fully Shielded $\beta = 8\ \mathrm{dB}$

Enclosed Source – Exposed Receiver

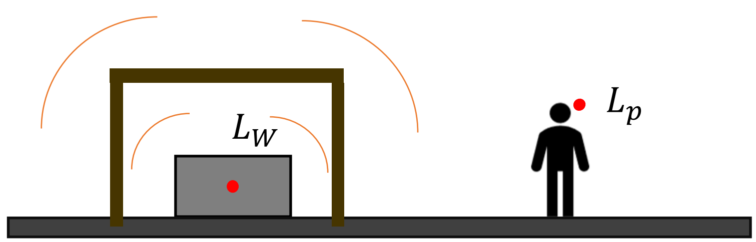
$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_r}\right) - SI_{diff} + 10\log\left(\frac{\Gamma_e \chi_{er}}{4\pi r_{er}^2}\right)$$

Enclosure Airspace

Panel Sound Isolation

Enclosure to Receiver Air Path

Enclosed Source – Exposed Receiver



Enclosed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_r}\right) - SI_{diff} + 10\log\left(\frac{\Gamma_e \chi_{er}}{4\pi r_{er}^2}\right)$$

Enclosure Airspace

Enclosure to Receiver Air Path

Near Field Adjustment

χ see earlier slide

se r is from source to enclosure
l_{max} is for source

er r is from enclosure to receiver
l_{max} is for enclosure dimension

Enclosed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_r}\right) - SI_{diff} + 10\log\left(\frac{\Gamma_e \chi_{er}}{4\pi r_{er}^2}\right)$$

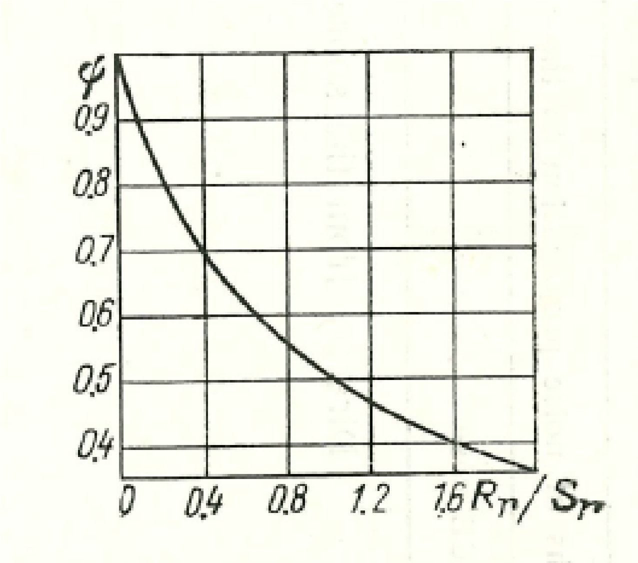
Enclosure Airspace

Diffuse Field Violation Adjustment

$$\psi = e^{-\frac{\sqrt{2}}{2}x} \qquad x = \frac{R_r}{S_r} = \frac{\bar{\alpha}}{1-\bar{\alpha}}$$

R_r Room constant for enclosure

S_r Surface area of enclosure



Enclosed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_r}\right) - \underline{SI_{diff}} + 10\log\left(\frac{\Gamma_e \chi_{er}}{4\pi r_{er}^2}\right)$$

Panel Sound Isolation

Sound Isolation of Panel

Normal Incidence

$$TL_{\perp} = 20\log_{10}(\rho_s f) - 42 \text{ dB}$$

Field Incidence

$$TL_{field} = TL_{\perp} - 5 \text{ dB}$$

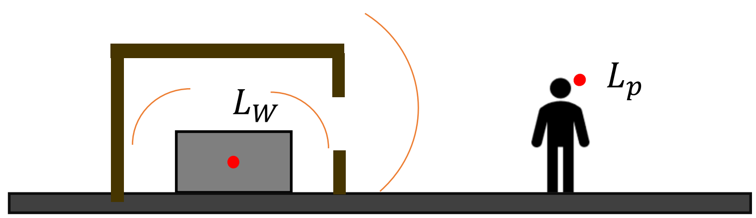
Partial Enclosed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_r}\right) + 10\log\left(\frac{S_o}{S_e}\right) + 10\log\left(\frac{\Gamma_e \chi_{er}}{4\pi r_{er}^2}\right)$$

Enclosure Airspace

Opening

Opening to Receiver Air Path



Partial Enclosed Source – Exposed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi}{R_r}\right) + 10\log\left(\frac{S_o}{S_e}\right) + 10\log\left(\frac{\Gamma_e \chi_{er}}{4\pi r_{er}^2}\right)$$

Opening

Opening Area

S_o Open Area
S_e Enclosure Area

Near Field Adjustment

χ see earlier slides

se r is from source to enclosure
l_{max} is for source

er r is from opening to receiver
l_{max} is the opening dimension

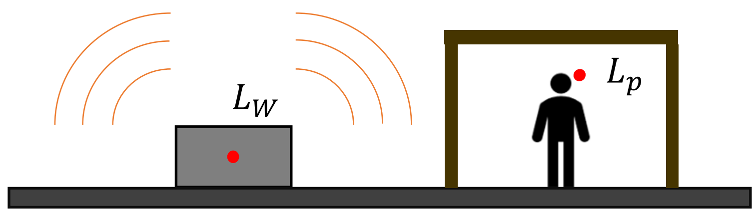
Exposed Source – Enclosed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2}\right) + DI - \beta - SI_{\perp} - \Lambda + 10\log\left(\frac{S_p}{R_r}\right)$$

Airborne Path from Source to Enclosure ($L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2}\right) + DI - \beta$)

Enclosure Walls ($SI_{\perp}$)

Enclosure Airspace ($\Lambda + 10\log\left(\frac{S_p}{R_r}\right)$)



Exposed Source – Enclosed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2}\right) + DI - \beta - \underline{SI_\perp} - \Lambda + 10\log\left(\frac{S_p}{R_r}\right)$$

Wall Sound Isolation

Sound Isolation of Panel

Normal Incidence

$$SI_\perp = 20\log_{10}(\rho_s f) - 42\ \text{dB}$$

Exposed Source – Enclosed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2}\right) + DI - \beta - SI_{\perp} \underline{- \Lambda +} 10\log\left(\frac{S_p}{R_r}\right)$$

Wall Location

Λ Addition to the Panel Sound Isolation

Distance from Source (m)	**Cab Panels**	**Frequency (Hz)**							
		63	125	250	500	1000	2000	4000	8000
0.1-2.0	Side	9	9	9	9	9	9	13	17
	Roof	5	9	9	12	12	12	15	18
	Back	11	14	14	14	14	14	17	20
> 2.0	Side	5	7	7	7	7	7	9	9
	Roof	6	8	8	8	8	8	10	10
	Back	5	11	11	13	13	13	18	18

Exposed Source – Enclosed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2}\right) + DI - \beta - SI_\perp - \Lambda + \underline{10\log\left(\frac{S_p}{R_r}\right)}$$

Enclosure
Airspace

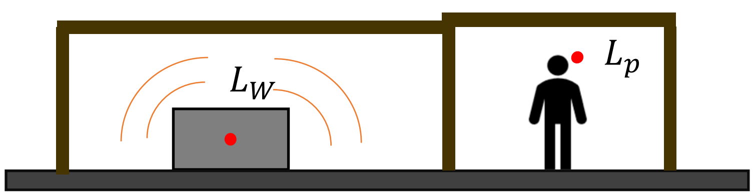
Variables

R_r	room constant for enclosure
S_p	surface area of panel

Enclosed Source – Enclosed Receiver

$$L_{P_{rec}} = \underbrace{L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_{re}}\right)}_{\text{Enclosure Airspace}} - \underbrace{SI_{panel}}_{\text{Panel Sound Isolation}} + \underbrace{10\log\left(\frac{S_p}{R_{rec}}\right)}_{\text{Receiver Room}}$$

with common wall



Enclosed Source – Enclosed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_{re}}\right) - SI_p + 10\log\left(\frac{S_p}{R_{rec}}\right)$$

Enclosure Airspace — Panel Sound Isolation — Receiver Room

Variables

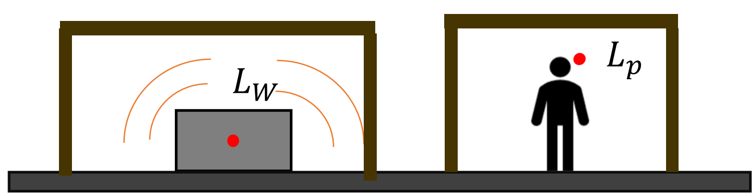
S_p	panel area
S_e	enclosure area
R_{re}	room constant for enclosure
R_{rec}	room constant for receiver room
SI_p	sound isolation of panel (normal incidence because of small receiver room or cab)

Enclosed Source – Enclosed Receiver

$$L_p = L_W + 10\log\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_{re}}\right) - SI_s + 10\log\left(\frac{\Gamma_s \chi_{er}}{4\pi r_{er}^2}\right) - SI_{rec} + 10\log\left(\frac{S_p}{R_{rec}}\right)$$

Enclosure Airspace | Source Enclosure Sound Isolation | Direct Field Enclosure to Receiver | Receiver Enclosure Sound Isolation | Receiver Room

no common wall



Combining Paths

$$L_p = 10\log_{10}\left(\sum_{i=1,N} 10^{\frac{L_{pi}}{10}}\right)$$

i	index for each path
N	number of paths

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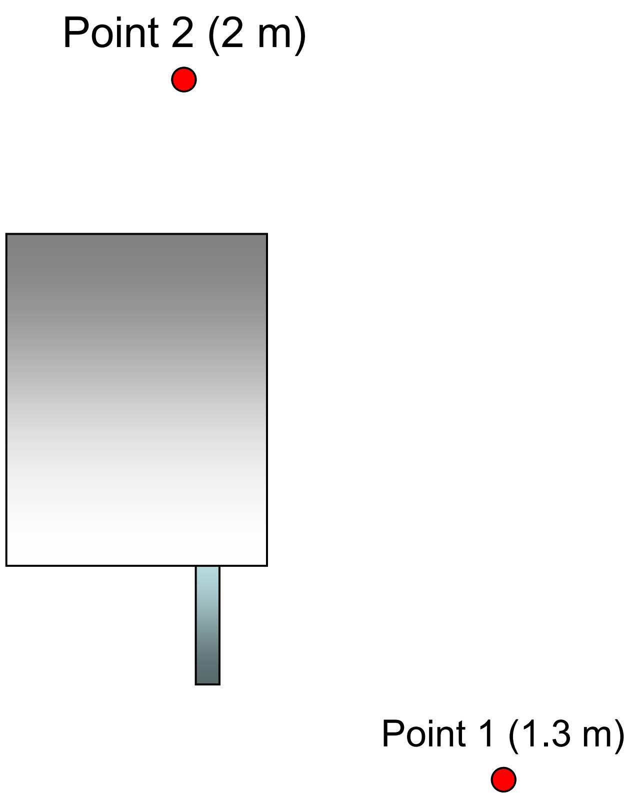
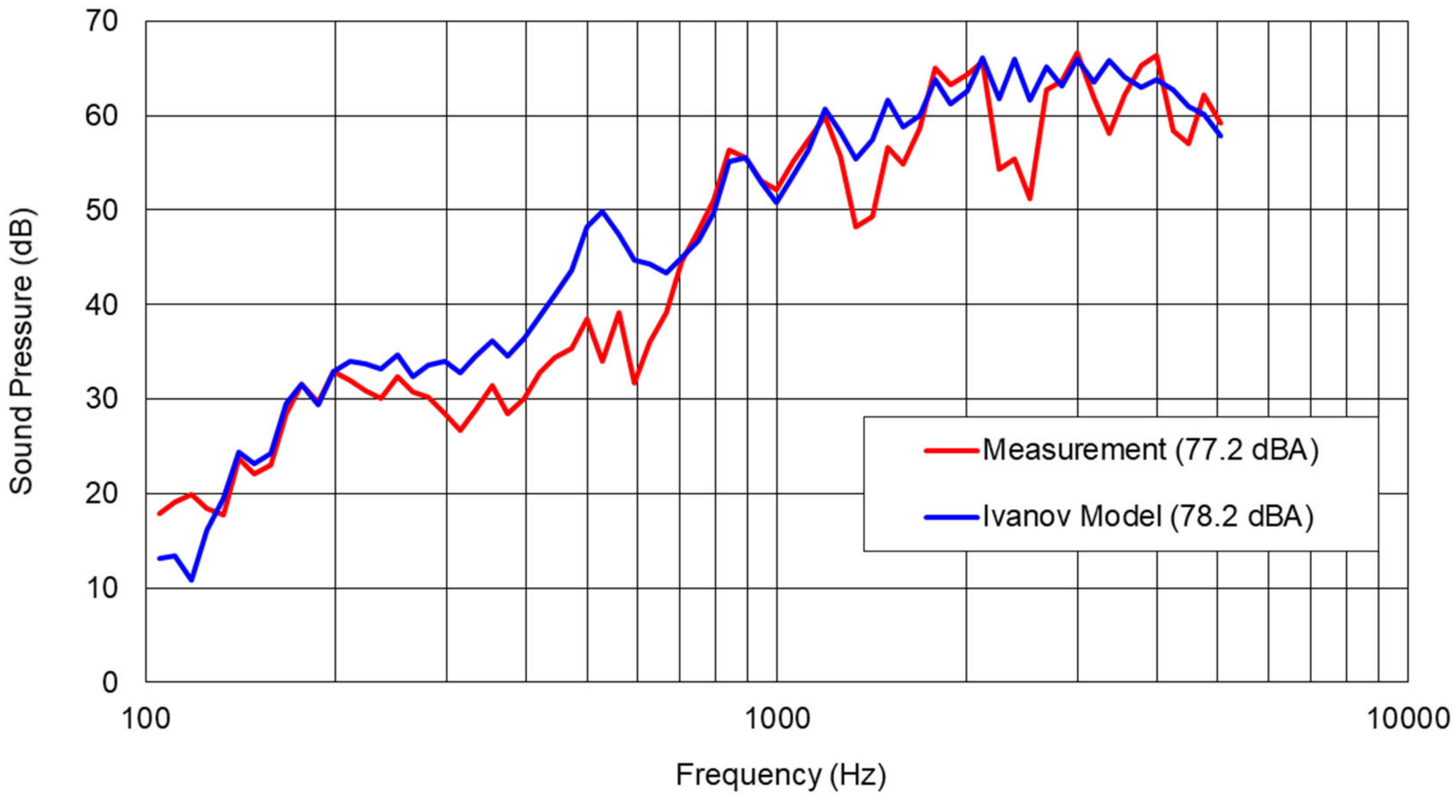
- Examples

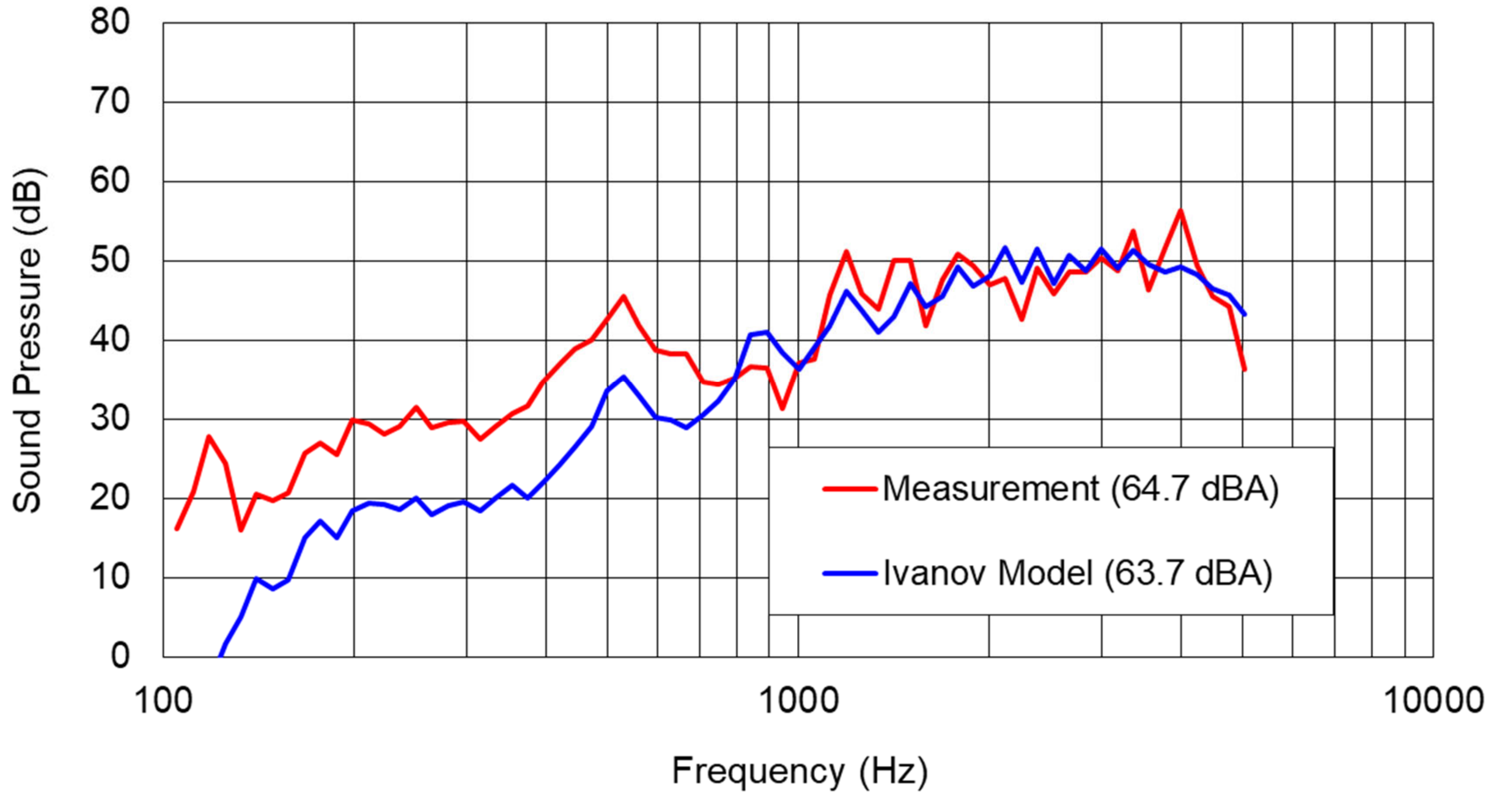
Exposed Source – Exposed Receiver



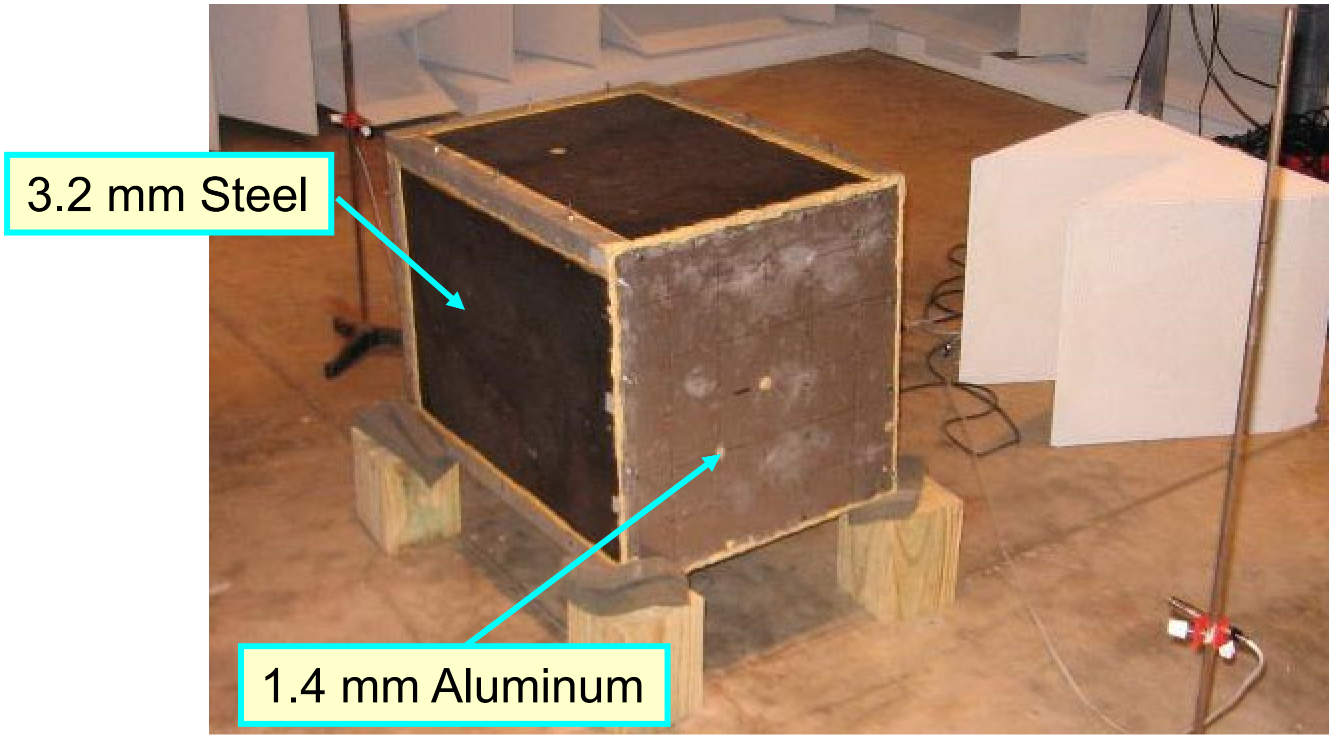
Sound Pressure Comparison Point 1



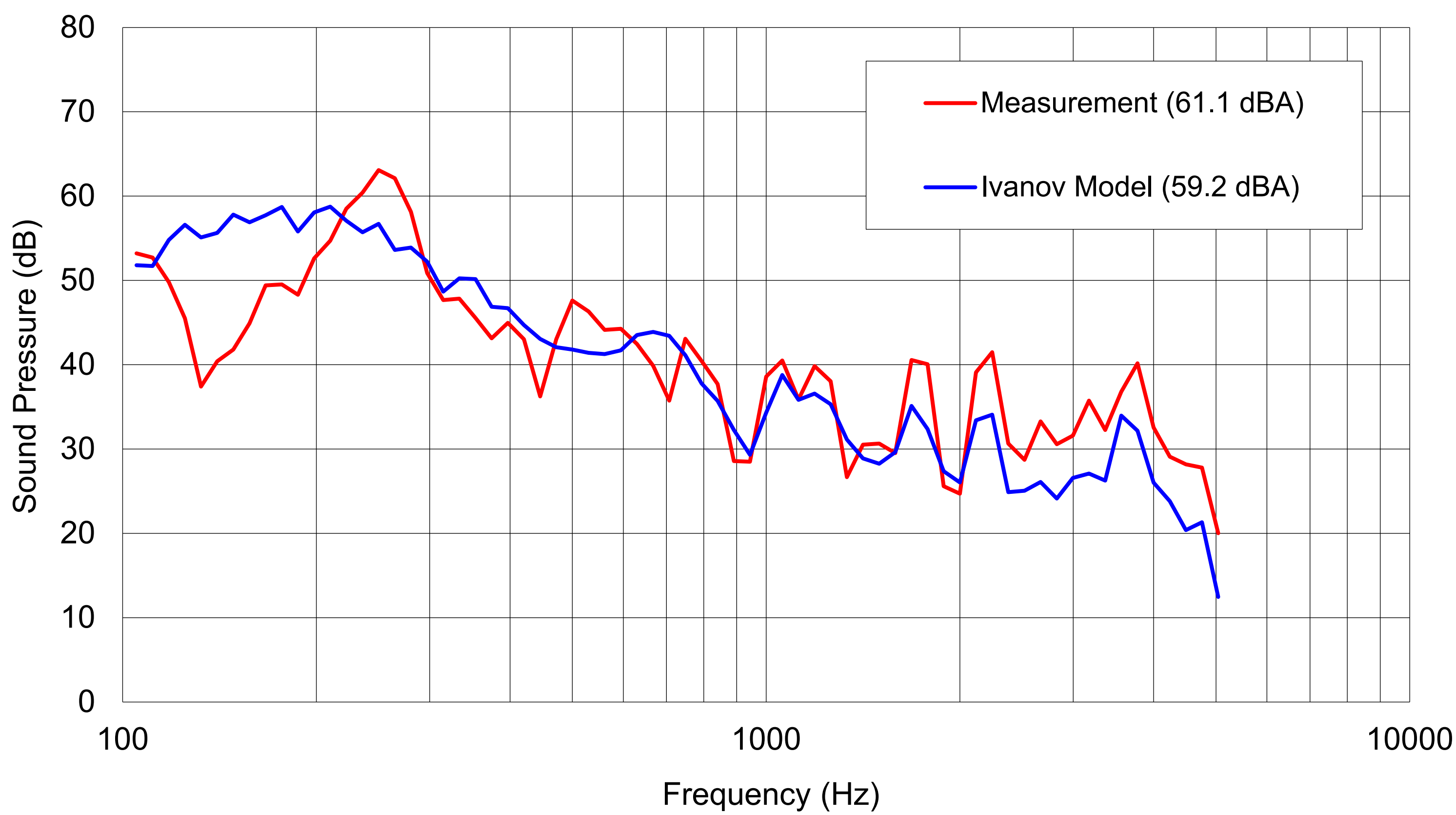
Sound Pressure Comparison Point 2



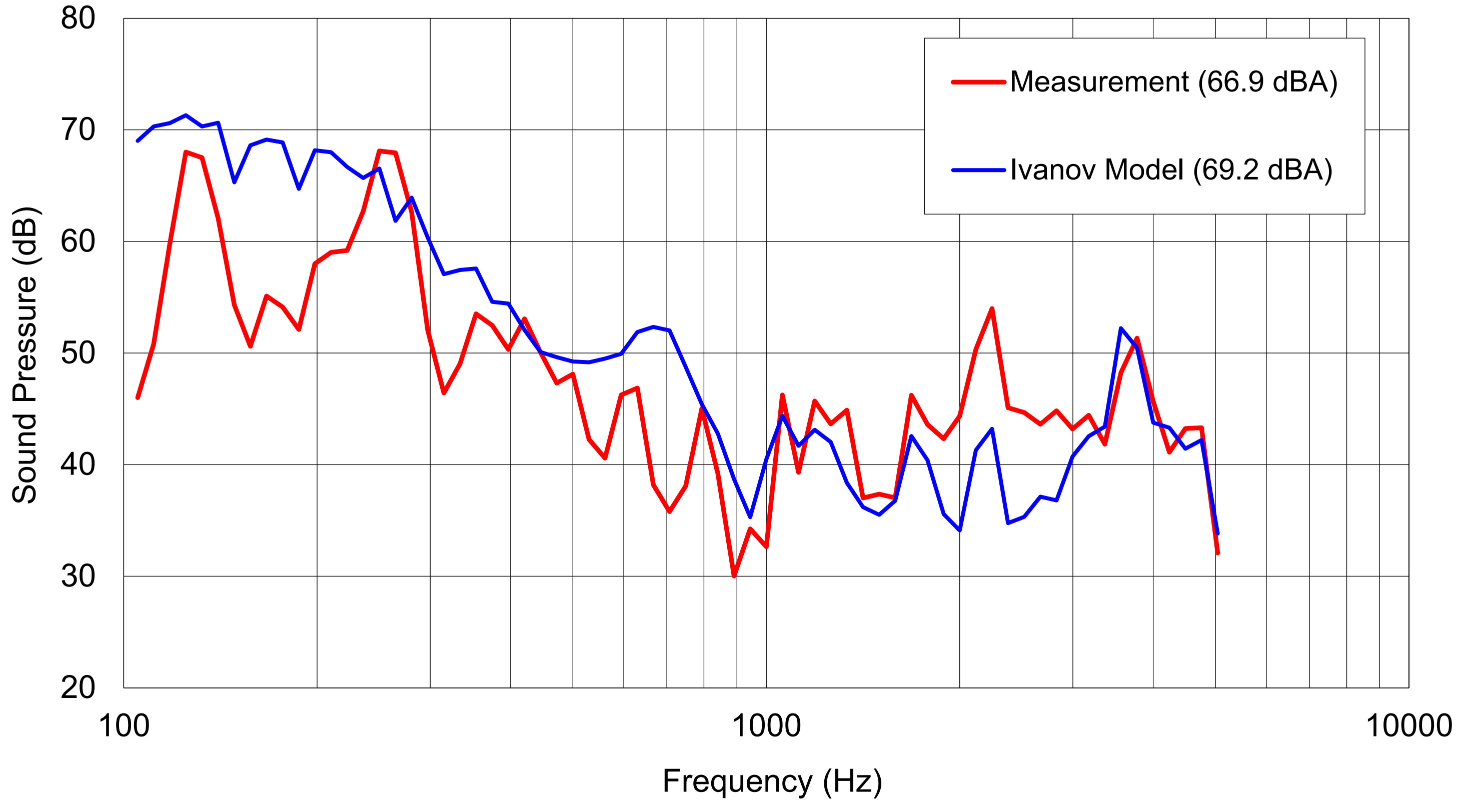
Enclosed Source – Enclosed Receiver



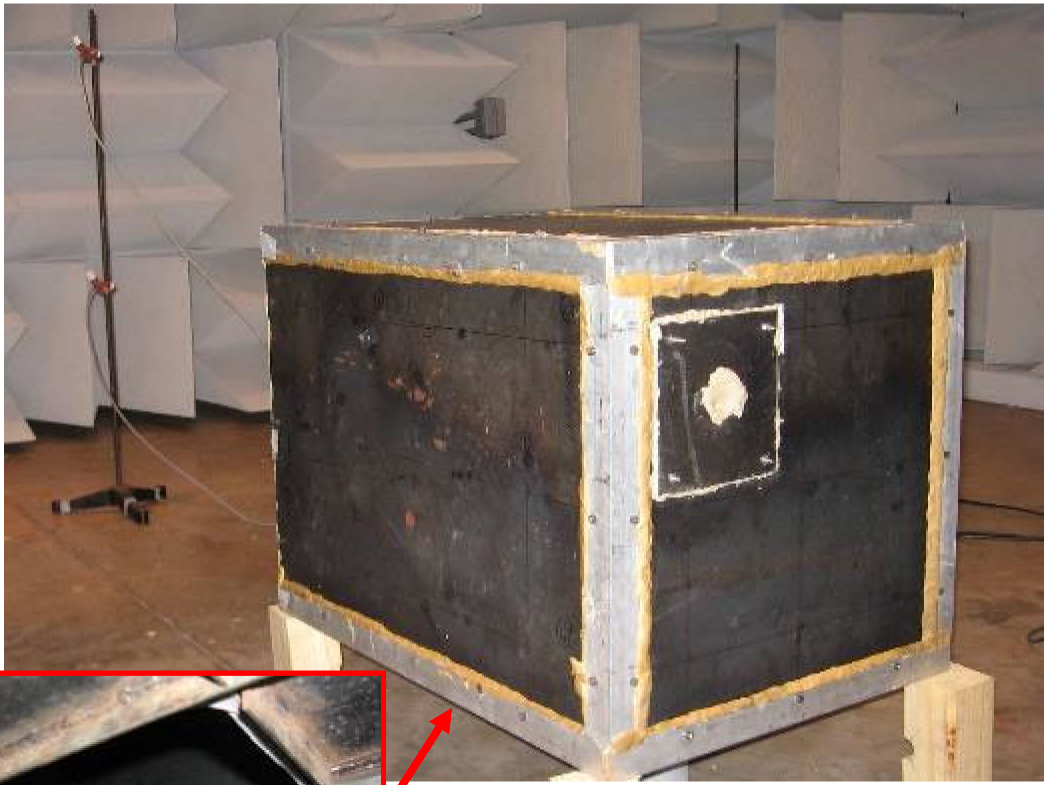
0.3 m from 3.2 mm Steel Panel



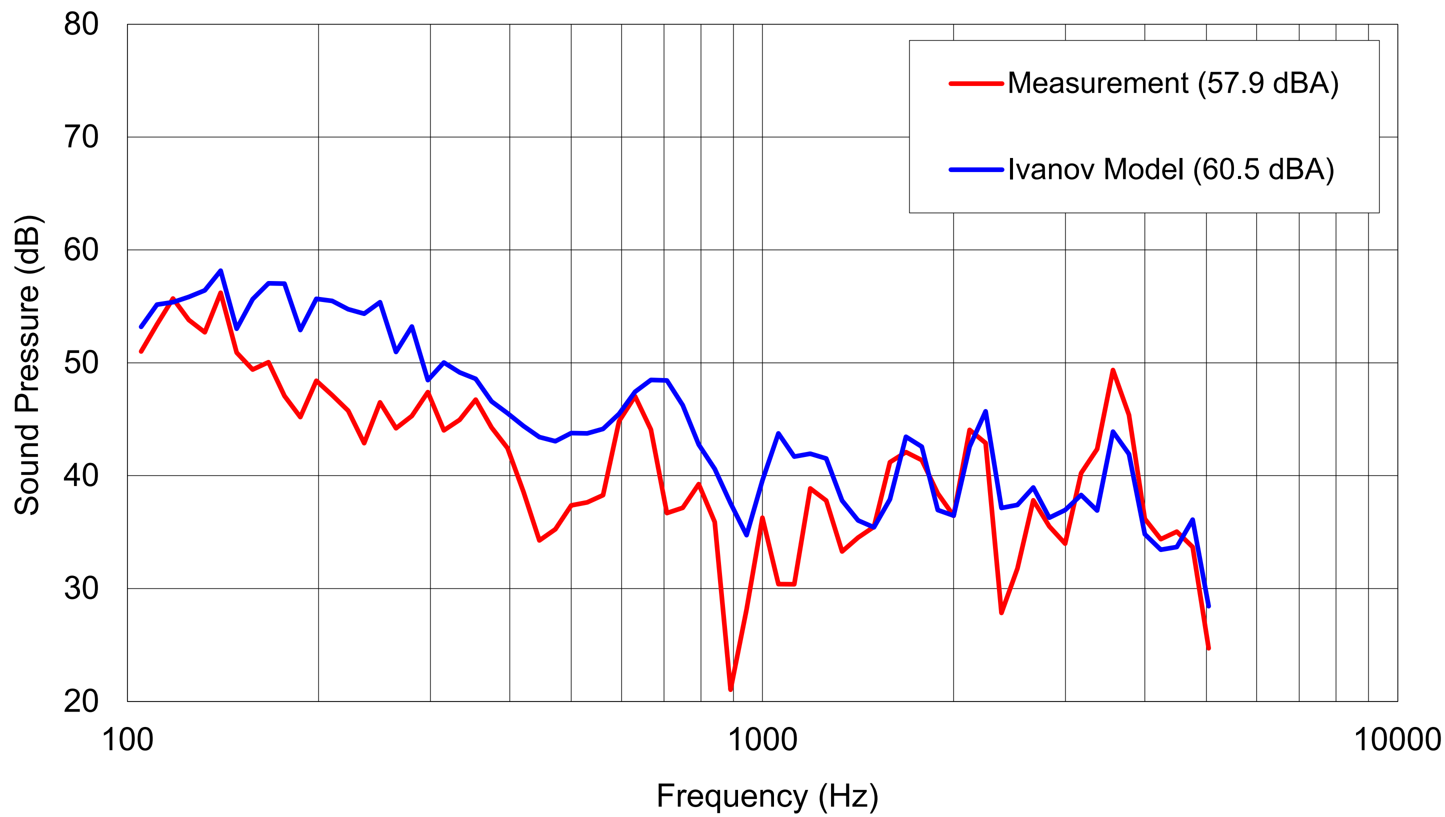
0.3 m from 1.4 mm Aluminum Panel



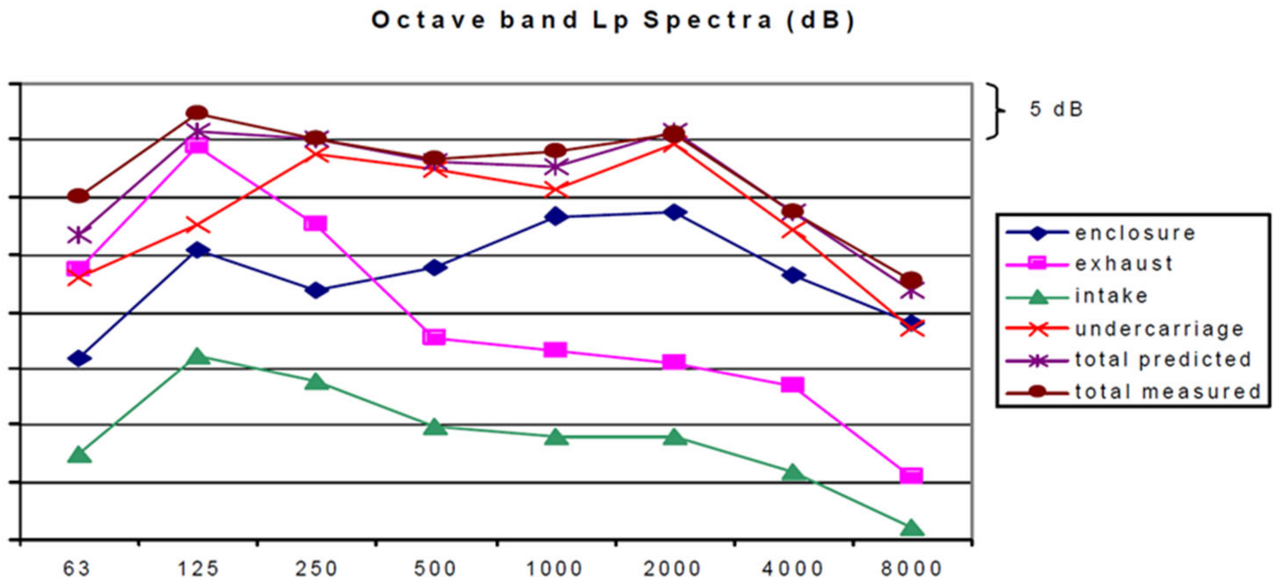
Partial Enclosed Source – Exposed Receiver



1.5 m from Enclosure

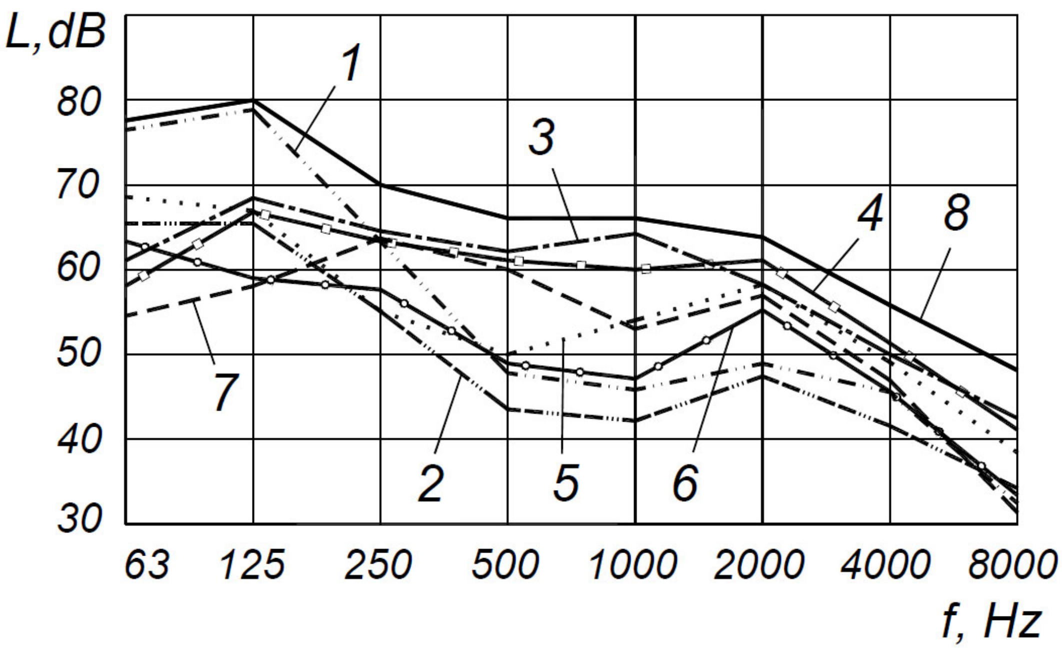


Tracked Dozer Exterior Noise



Ivanov et al., 2002

Tracked Dozer Interior Noise



Ivanov and Copley, 2005

1. Exhaust noise.
2. Intake noise.
3. Diesel noise propagating though the partition between the engine compartment and the cab.
4. Diesel noise propagating through enclosure underneath the opening.
5. Diesel compartment noise propagating though the enclosure panels.
6. Undercarriage noise propagating through the cab panels.
7. Undercarriage noise propagating through the cab floor.
8. Total airborne interior sound field of a tracked dozer.

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