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A Simple Spreadsheet Tool for Noise Path Characterization

This paper is condensed from Reference [1].

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ABSTRACT
Many industries, like aerospace and automotive, are well staffed and are equipped to consider noise control even in the early product development stages. However, noise control practice is inadequate in many industrial sectors including textile, paper, metal fabrication, and food preparation. The objective of this work is to develop a simple spreadsheet tool that can be used to predict the effectiveness of common noise control measures. Though some basic noise control knowledge is needed, the user need not be a noise control expert. The methods and relevant theory are described, and the model is tested on several examples.

1 INTRODUCTION
Many industries are ill equipped to consider noise control in the early design stages. This is especially the case for manufacturing and food preparation equipment. Workers are commonly exposed to high noise levels since mitigation measures have not been considered in the design stages. However, engineers designing the equipment and the in-plant personnel have little noise control experience.

The intent of this work is to acquaint the reader with simple room acoustics models supplemented with empirical data first suggested by Nickolay Ivanov and Gennady Kurtsev over 25 years ago [2]. This approach has been utilized extensively for heavy equipment by Ivanov and Copley [3-12]. The models are appealing because they can be easily implemented into spreadsheet form and are simple enough to be used by consultants and engineers with some noise control experience. Moreover, users do not need expensive measurement equipment to put the approach into practice.

The model employs a source-path-receiver energy accounting approach. General forms for common paths are used as approximations, but it is preferable that paths be validated experimentally and adjusted for a given application. Moreover, the model can be incrementally improved over time, and more sophisticated simulation or experimental models can be integrated into the spreadsheet framework.

The model is statistical in nature and disregards the wave nature of sound except for some correction terms. The assumptions that the model is based on are as follows [2,13].

1. Sound sources are incoherent, and the acoustic signals are wide band. Sound sources distributed at distances greater than λ/6 may be considered incoherent where λ is the acoustic wavelength.
2. 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 10th acoustic mode.
3. Sound pressure at any specific point is determined by the energy summation principle.
4. Resonance phenomena are ignored as a rule.
5. Sources generate sound fields which are idealized as spherical, cylindrical, or plane wave.

In the sections that follow the model will be described and then illustrated for heavy equipment.

2 DESCRIPTION OF THE MODEL

The models suggested by Ivanov and Kurtsev [2] are simple expansions of room acoustics theory which is reviewed in brief. The sound pressure level in a room is a combination of the direct and reverberant fields. The direct field is that produced when the source is placed in an anechoic environment (no reflections) whereas the reverberant field is due to the reflected sound from walls, floor, and ceiling. According to room acoustics theory [14], the sound pressure level (L_p) at a given position can be expressed as

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

where L_W is the sound power level of the source, r is the distance from the source, and R_r is the room constant. Γ considers if the source is close to a single plane or multiple planes. $\Gamma = 1$ if the source is in a free field. Γ=2 if the source is located close to a single plane (i.e. sitting on the ground). $\Gamma = 4$ if the source is adjacent to two planes (the edge of a room). Γ=8 if the source is close to three planes (a corner of a room). The model can be tuned to match experimental data by adjusting Γ.

The room constant is expressed as

$$R_r = \frac{\langle\alpha_d\rangle S}{1 - \langle\alpha_d\rangle} \quad (2)$$

where S is the surface area of the space and $\langle\alpha_d\rangle$ is the spatially averaged sound absorption coefficient in the room. The spatially averaged sound absorption can be determined using

$$S\langle\alpha_d\rangle = S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n \quad (3)$$

where S_i and α_i are subareas and respective sound absorption coefficients, and n is the total number of subareas. Sound absorption coefficients can be found in textbooks for some standard materials.

The sound transmission coefficient through a wall or panel can be expressed as

$$\tau = \left(\frac{2\rho c S_p}{m\omega}\right)^2 \quad (4)$$

where ρ and c are the density and speed of sound or air, ω is the angular frequency in rad/s, and m is the mass of the panel. For composite panels or walls manufactured from different materials, the composite transfer function τ_{eq} is expressed as

$$S_p\tau_{eq} = S_1\tau_1 + S_2\tau_2 + \cdots + S_n\tau_n \quad (5)$$

where S_i and τ_i are subpanel areas and subpanel transmission coefficients respectively. n is the total number of subpanels. The sound isolation for normal incidence can be expressed in terms of the transmission coefficient as

$$SI_{\perp} = 10\log_{10}\left(\frac{1}{\tau_{eq}}\right) \tag{6}$$

and the field incident transmission loss can be written as

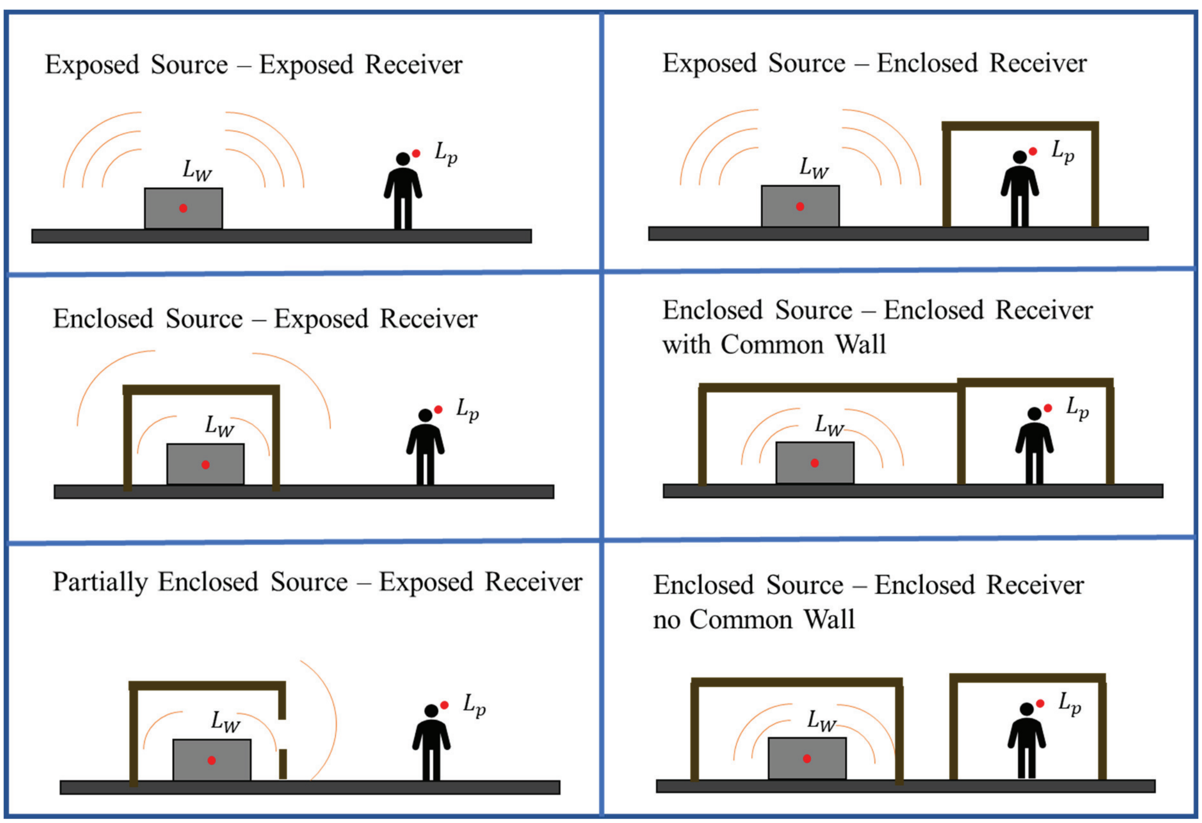
$$SI_{diff} = SI_{\perp} - 5 \tag{7}$$

where either Equation (6) or Equation (7) can be used in the equations which follow depending on which is more appropriate for the case being considered.

3 SOUND PROPAGATION MODELS

Sound propagation models are detailed for each of the 6 cases shown in Table 1. Additional models have been developed by Ivanov and Kurtsev [1]. These are the most common and deal with many common cases that are encountered in industries lacking NVH expertise.

Table 1: Sound propagation cases.



3.1 Exposed Source – Exposed Receiver

The case of an exposed source and receiver is considered first. The sound pressure level at the receiver position can be expressed as

$$L_p = L_W + 10\log_{10}\left(\frac{\Gamma\chi}{4\pi r^2}\right) + DI - \beta \tag{8}$$

where χ is a near field correction. The near field correction can be expressed as

$$\chi = 2.5 + 1.5\cos\left(\frac{\pi}{2}\frac{r}{l_{max}}\right) \tag{9}$$

where l_{max} is the maximum dimension of the source if $r/l_{max} < 2$. If $r/l_{max} > 2$, then $\chi = 1$. Equation (8) is based on the correction curve developed by Ivanov [2]. DI is a directivity index. If the sound source is aimed towards or away from the receiver, $DI = 4$ dB or $DI = -4$ dB respectively. β is a source shielding term. $\beta = 5$ dB if the source is partially shielded and $\beta = 8$ dB if the source is fully shielded. Notice that the second term on the right-hand side is a direct field term, and the third and fourth terms are adjustments.

3.2 Enclosed Source – Exposed Receiver

The case of an enclosed source and exposed receiver is considered. The sound pressure level at the receiver can be expressed as

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

where r_{se} and r_{er} are respective distances from source to enclosure and from enclosure to receiver. The near field correction terms χ_{se} and χ_{er} are based on the source to enclosure and enclosure to receiver distances respectively. R_r is the room constant for the enclosure. Γ_s and Γ_e are symmetry terms for the source and enclosure respectively.

ψ is a correction term that accounts for differences from room acoustics theory in the enclosure. If the enclosure has high sound absorption, room acoustics theory will no longer be entirely valid since the sound field inside the room will not be diffuse. This correction term is developed from reference [1] and can be expressed as

$$\psi = e^{\frac{\sqrt{2}}{2}x_\psi} \tag{11}$$

where

$$x_\psi = \frac{\langle\alpha_d\rangle}{1 - \langle\alpha_d\rangle} \tag{12}$$

with $\langle\alpha_d\rangle$ equal to the spatially averaged sound absorption in the enclosure.

Examining Equation (10), it can be observed that the equation includes the source to enclosure path (the second term on the right hand side), the sound isolation (SI_{diff}) of the enclosure, and the enclosure to receiver path (the last term on the right hand side). Also, the enclosure correction term in Equation (11) will usually only change results by a few dB and will be unimportant in many cases.

3.3 Partially Enclosed Source – Exposed Receiver

The expression for a partially enclosed source and exposed receiver is similar to that for the fully enclosed source given in Equation (10) except that the panel transmission loss term is replaced by a term to account for the size of the opening. The sound pressure level is expressed as

$$L_p = L_W + 10\log_{10}\left(\frac{\Gamma_s\chi_{se}}{4\pi r_{se}^2} + \frac{4\psi}{R_r}\right) + 10\log_{10}\left(\frac{S_o}{S_e}\right) + 10\log_{10}\left(\frac{\Gamma_e\chi_{er}}{4\pi r_{er}^2}\right) \tag{13}$$

where S_o is the opening cross-sectional area and S_e is the surface area of the enclosure itself, r_{er} is the distance from the enclosure opening to the receiver, and χ_{er} is the diffuse field violation correction term.

3.4 Exposed Source – Enclosed Receiver

The sound pressure level for an exposed source and enclosed receiver can be expressed as

$$L_p = L_W + 10\log_{10}\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2}\right) + DI - \beta - SI_{\perp} - \Lambda + 10\log_{10}\left(\frac{S_p}{R_r}\right) \tag{14}$$

where the first four terms on the right hand side are identical to Equation (8), $SI_{\perp}$ is the sound isolation of the panel for normal incidence, S_p is the surface area of a panel, and R_r is the room constant of the enclosure. r_{se} is the distance from the source to the receiving enclosure and χ_{se} is calculated using this distance. Λ is an addition to the panel sound isolation depending on where the receiver panel is located. Values for Λ are defined in Refs. [1-2]. Equation (14) may be applied panel by panel. However, Λ values are sufficiently large that sound transmission through the panel nearest the receiver should be the most important path unless that panel is significantly more massive than neighbouring panels.

3.5 Enclosed Source – Enclosed Receiver with Common Wall

The sound pressure level for an enclosed source and enclosed receiver with a common wall can be expressed as

$$L_p = L_W + 10\log_{10}\left(\frac{\Gamma_s \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_{sou}}\right) - SI_p + 10\log_{10}\left(\frac{S_p}{R_{rec}}\right) \tag{15}$$

where S_p is the panel area and R_{sou} and R_{rec} are the room constants for the source and receiving enclosures respectively. ψ_{sou} is the diffuse field violation for the source enclosure. All other terms have been described earlier.

3.6 Enclosed Source – Enclosed Receiver without Common Wall

The sound pressure level for an enclosed source and enclosed receiver with no common wall can be expressed as

$$\begin{aligned} L_p = L_W &+ 10\log_{10}\left(\frac{\Gamma \chi_{se}}{4\pi r_{se}^2} + \frac{4\psi_{se}}{R_{sou}}\right) - SI_{se} + 10\log_{10}\left(\frac{\Gamma \chi_{er}}{4\pi r_{er}^2}\right) - SI_{rec} \\ &+ 10\log_{10}\left(\frac{S_p}{R_{rec}}\right) \end{aligned} \tag{16}$$

where the subscript er refers to the path from source enclosure to receiver enclosure. SI_{se} and SI_{rec} refer to the sound isolation of the source and receive enclosures respectively.

3.7 Combining Sources

The spreadsheet model developed should be applied path by path. The contributions from each path can be added together to determine the total contribution. Accordingly, the sound pressure level at a given position can be expressed as

$$L_p = 10\log_{10}\left(\sum_{i=1,N} 10^{\frac{L_{pi}}{10}}\right) \tag{17}$$

where L_{pi} is the contribution from path i assuming there are N total paths. Often, the dominant path will be relatively obvious to identify and then it is only a matter of examining the equation for one particular path.

4 CONSTRUCTION EQUIPMENT APPLICATIONS

A variation of the spreadsheet model presented in this work has been applied extensively to construction equipment by Ivanov and Copley [4-12]. That body of work is useful for demonstrating how the model can be customized to particular equipment types.

For example, the main noise contributions to the interior cabin noise are illustrated in Figure 1. These include the:

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.

The sound pressure level from the combined sources can be determined using Equation (17). It can be implied that the main contributions are through the partition between the cab and diesel engine compartment and from the engine noise propagating though the opening underneath the engine compartment. It follows that the noise could be reduced by increasing the sound isolation of the partition and by redirecting the noise from the opening.

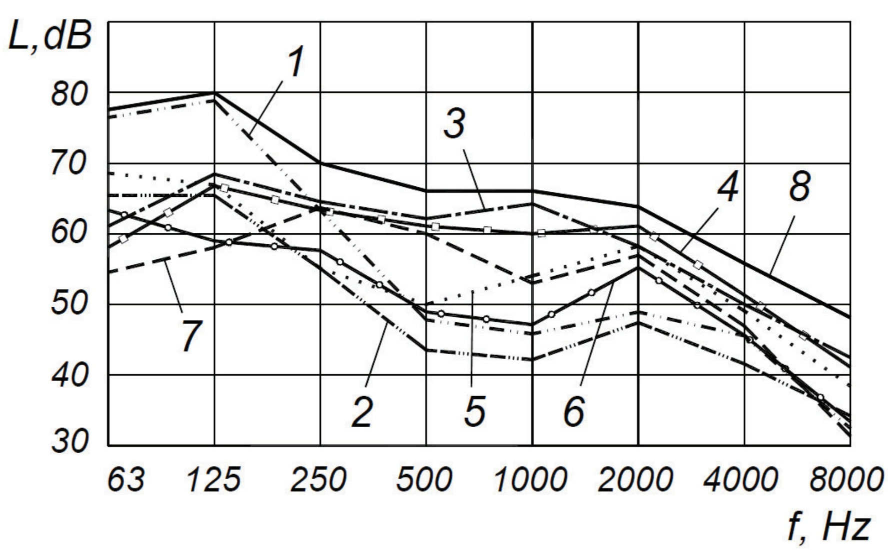


Figure 1: *Example of theoretically predicted interior noise spectrum of a tracked dozer [8].*

Figure 2 shows a similar prediction for the contributions from the individual components to the sound pressure levels 7.5 m from a dozer tractor. The prediction correlates well with direct measurement, and it can be concluded that the undercarriage noise is the most prominent noise source and should be addressed first. Simple models like this in the early design stages can be used to identify and communicate dominant sources and paths in order to establish component targets and mitigation plans.

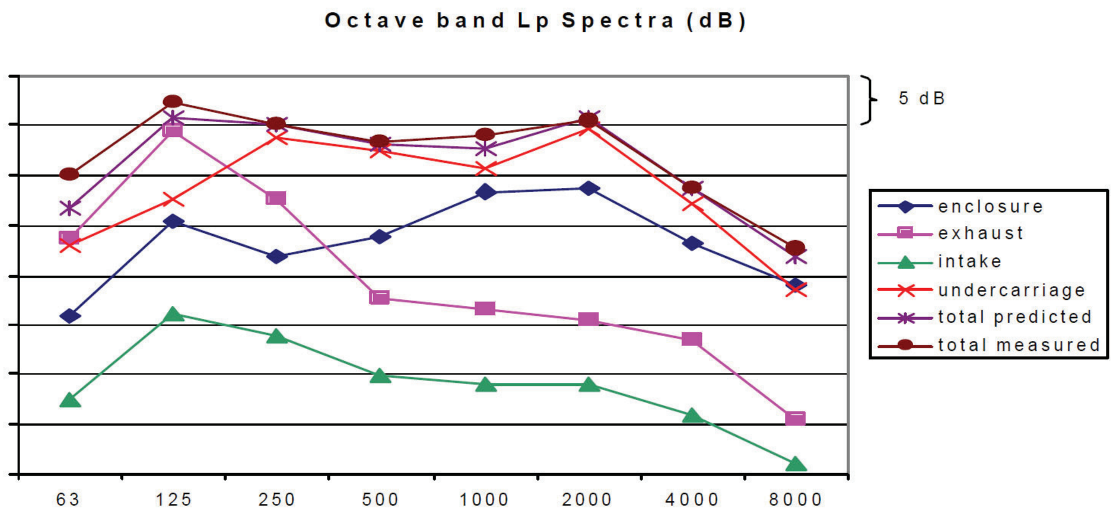


Figure 2: *Predicted sound pressure level contributions for dozer tractor at 7.5 m away [4].*

5 CONCLUSIONS

In summary, equations for simple spreadsheet models to identify the contributions to the sound pressure level have been reviewed and detailed. Further details are available in Reference [2]. The spreadsheet model can be easily customized to the equipment of interest, and the model seems ideal for evaluating noise contributions from manufacturing and food processing equipment. The models can be enhanced to include barriers and structureborne paths. The authors have a spreadsheet that can be shared upon request.

6 ACKNOWLEDGEMENTS

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