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Indoor-Outdoor Method for Measurement of Noise Reduction

August 2023

Final Report

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16. Abstract

In 2014, the Federal Aviation Administration (FAA) amended the Airport Improvement Program (AIP) Handbook to clarify guidance for the funding of noise mitigation projects. The clarification addressed requirements that structures eligible for sound insulation treatment not only be located within the day-night average sound level (DNL) 65-decibel (dB) noise contour, but also experience existing interior noise levels that are 45 dB or greater with the windows closed. This restated guidance placed greater emphasis on the accuracy in measuring the existing noise reduction of a structure.

Subsequent research by the FAA to develop best practices for measuring the aircraft noise reduction of building facades has resulted in the development of a new SAE Recommended Practice, ARP 6973, that provides additional details for application to practical situations. Like its predecessor, ASTM E966, the method requires the use of an outdoor loudspeaker. However, there are situations encountered in the field, such as areas with limited exterior space, where it is either difficult to actually position a loudspeaker, or to generate a uniform distribution of sound energy over the test facade.

In an attempt to overcome these limitations, an alternative method for measuring noise reduction was investigated, with a loudspeaker placed inside the house and the noise reduction measured from the inside to the outside. This approach removes restrictions on the placement of an external loudspeaker. The goal of this project was to conduct a feasibility study of such an indoor-outdoor test procedure for measuring noise reduction in buildings.

Following a series of preliminary parameter tests designed to provide the necessary details to define an indoor-to-outdoor (I-O) test procedure, field measurements were conducted in 10 rooms of three houses to demonstrate equivalence of the results with those of the standard outdoor-to-indoor (O-I) method. The differences between the O-I and I-O measured values of noise reduction for the 10 rooms tested were all well within ±1 dB, the average difference being 0.1 dB.

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LIST OF ACRONYMS

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
ACRP	Airport Cooperative Research Program
ARP	Aerospace Recommended Practice
ASTM	American Society for Testing and Materials
DI	Directivity index
DNL	Day-night average sound level
FAA	Federal Aviation Administration
I-O	Indoor-outdoor
ISO	International Organization of Standardization
LS	Loudspeaker
mks	Meter (length), kilograms (mass), and seconds (time)
NLR	Noise level reduction
O-I	Outdoor-indoor
RSS	Reference sound source
SAE	SAE International, formerly the Society of Automotive Engineers

EXECUTIVE SUMMARY

In 2014, the Federal Aviation Administration (FAA) amended the Airport Improvement Program (AIP) Handbook to clarify guidance for the funding of noise mitigation projects. The clarification addressed requirements that structures eligible for sound insulation treatment not only be located within the day-night average sound level (DNL) 65-decibel (dB) noise contour, but also experience existing interior noise levels that are 45 dB or greater with the windows closed. This restated guidance placed greater emphasis on the accuracy in measuring the existing noise reduction of a structure.

Subsequent research by the FAA to develop best practices for measuring the aircraft noise reduction of building facades has resulted in the development of a new SAE Recommended Practice, ARP 6973, that provides additional details for application to practical situations. Like its predecessor, ASTM E966, the method requires the use of an outdoor loudspeaker. However, there are situations encountered in the field, such as areas with limited exterior space, where it is either difficult to actually position a loudspeaker, or to generate a uniform distribution of sound energy over the test facade.

In an attempt to overcome these limitations, an alternative method for measuring noise reduction was investigated, with a loudspeaker placed inside the house and the noise reduction measured from the inside to the outside. This approach removes restrictions on the placement of an external loudspeaker. The goal of this project was to conduct a feasibility study of such an indoor-outdoor test procedure for measuring noise reduction in buildings.

Following a series of preliminary parameter tests designed to provide the necessary details to define an indoor-to-outdoor (I-O) test procedure, field measurements were conducted in 10 rooms of three houses to demonstrate equivalence of the results with those of the standard outdoor-to-indoor (O-I) method. The differences between the O-I and I-O measured values of noise reduction for the 10 rooms tested were all well within ±1 dB, the average difference being 0.1 dB.

Further development of the procedure is required before it can be incorporated into a future update of SAE ARP 6973 as an alternative or supplemental method for measurement of building noise reduction. Follow-on research began at the time of this publication.

1. INTRODUCTION

Current research by the Federal Aviation Administration (FAA) to develop best practices for measuring the aircraft noise reduction of building facades has resulted in the development of a new SAE International (SAE) Recommended Practice (Aerospace Recommended Practice [ARP] 6973) to determine the eligibility of noise impacted structures for participation in an Airport Noise Compatibility Program/Sound Insulation Treatment Program. One method defined in ARP 6973 is widely used today for measuring the noise reduction of a building facade by placing a loudspeaker outside the building and measuring the difference between the exterior and interior noise levels. Like its predecessor, American Society for Testing and Materials (ASTM) E966-18a (ASTM, 2018), the method requires applying adjustment factors to the exterior noise level measurements to account for the reflection of sound energy from the facade surface. However, there are situations encountered in the field, such as areas with limited exterior space, where it is either difficult to actually position a loudspeaker, or to generate a uniform distribution of sound energy over the test facade.

To overcome these limitations, an alternative method for measuring noise reduction has been proposed, where a loudspeaker is placed inside the house, and the noise reduction is measured from the inside to the outside. This approach eliminates the need for any adjustments to the measured levels and removes restrictions on the placement of an external loudspeaker. The indoor-to-outdoor (I-O) method also has the advantage that the contribution to the overall noise reduction from different facade elements (i.e., windows and doors.) can be directly measured. This information can be useful in designing noise reduction strategies, and in selecting appropriate noise reduction materials. An interior loudspeaker also eliminates noise complaints from nearby residents. Previous Airport Cooperative Research Program (ACRP)-sponsored research has highlighted the need for further investigation into the feasibility of an I-O testing method.

The goal of this project was to conduct a feasibility study of a procedure for measuring noise reduction in buildings using an I-O test configuration. With initial success, the long-term plan is to further develop the procedure so that it can be considered as an alternative or supplemental method in a future update of the ARP 6973, *Aircraft Noise Level Reduction Measurement of Building Facades*.

2. LITERATURE REVIEW AND ANALYSIS

2.1 INTRODUCTION

As part of the development of ARP 6973, research included a review and analysis of the previous work on the generation, propagation, and transmission of noise in buildings, specifically directed at defining the outdoor-indoor (O-I) measurement procedure. Such a volume of literature does not exist for an I-O test procedure.

The earliest reference to an I-O procedure for measuring noise reduction appears in an article by Sharp (1996), who presents the results of measurements in 22 units of an apartment building located near a major airport. With a loudspeaker inside the test room, sound levels were measured in the interior reverberant field and by a two-dimensional (2D) scan close to the exterior facade. The difference between the two measurements, with a correction for room absorption applied, was used to define the noise reduction. A comparison of the differences between these measurements and those from aircraft overflights showed a standard deviation of 2 decibel (dB), i.e., 95% of the differences were within ±4 dB. Repeated tests of the I-O procedure conducted by different engineers in one of the residences indicated that the repeatability was ±0.5 dB. No comparison was made with O-I testing in the study.

The I-O procedure was further examined by Gurovich, et al. (2004), who compared the results with those obtained using aircraft overflights, with corrections applied for the shielding effects on facades not directly exposed. A correction for frequency spectrum, based on a portion of the collected data, was also applied to the measured data. The resulting data showed an uncertainty estimated to be 0.9 dB for the 95% confidence interval. However, the correctional data was developed specifically for the rooms tested. The authors state that the uncertainty in the results will likely be higher if the correctional data is applied toother data sets. Again, no comparison was made with O-I testing in the study.

Summarizing this very limited set of data, it is possible to conclude that, although the I-O test procedure, as it was implemented in the referenced studies, did not provide a close reasonable comparison with that from aircraft overflights, the repeatability of the procedure was high. It should be noted that, at the time these studies were conducted, the more rigorous guidance criteria for participation in an airport sound insulation program had not been clarified. As noted in ASTM E966-10$^{\varepsilon 1}$ (ASTM, 2010), the primary concern of the noise testing was to ensure that the application of sound insulation modifications achieved a reduction in interior noise level of at least 5 dB. Subsequent clarifications to the eligibility criteria (FAA, 2014) place greater emphasis on the accuracy of the measurement of the existing noise reduction of a structure, requiring a re-evaluation of the I-O test procedure.

The development of an I-O procedure for measuring noise reduction is an attempt to provide an update to the current SAE Recommended Practice ARP 6973 for situations that limit the use of an outdoor loudspeaker. Unlike the O-I method of ARP 6973, the I-O method does not simulate a real situation (namely, an external facade exposed to a noise source, such as a loudspeaker or an aircraft). Whether the value of noise reduction measured by the I-O method is equivalent to that measured using an exterior loudspeaker remains to be investigated.

While there is a lack of work on the actual measurement of noise reduction using an I-O procedure, there is previous work on the analysis of sound in rooms, the influence of room absorption, and the radiation of sound from exterior surfaces—all of which are applicable to the development of an I-O test that can simulate the results of the O-I procedure. The following sections describe the results of a literature review and analysis of publications and data related to the elements required for I-O measurement of noise reduction.

2.2 SOUND FIELDS IN ROOMS

The I-O method requires measurements of interior and exterior sound levels, so it is necessary to understand the characteristics of the interior and exterior sound fields generated by an interior loudspeaker so that suitable loudspeaker and measurement configurations can be selected.

The natural sound field in a room is a special-case solution of the three-dimensional (3D) general wave equation with boundary conditions imposed by the six walls. At low frequencies, the sound field is dominated by the energy in the natural resonant frequencies of the enclosure, commonly referred to as room modes. In this low-frequency range, these modes do not overlap, resulting in a sound pressure that varies considerably both from point to point and with changing frequency. As the frequency is increased, the number of modes increase and begin to overlap such that the sound pressure is more constant with position and frequency. It is important to understand this behavior with frequency in order to select the appropriate noise source and sound level measurement configurations as part of an I-O test procedure for measuring noise reduction, as well as to develop a relationship between measurements using this procedure and those from the corresponding O-I procedure.

2.2.1 Low-Frequency Modal Response of Rooms

The general wave equation for the propagation of a sound wave due to the presence of a source is (Morse, 1948):

$$\nabla^2 p - \frac{1}{c^2}\frac{d^2 p}{dt^2} = -\rho \frac{dq}{dt} \tag{1}$$

where p is the sound pressure, ρ is the density of air, c is the speed of sound in air, and q is a measure of source strength, expressed in terms of volume velocity. By treating the reduced equation in which the right-hand member is zero, the fundamental characteristics of the room can be calculated. In this manner, a solution to Equation (1) can be written as:

$$p(x,y,z,t) = Ae^{-i(\omega t + k_x x + k_y y + k_z z)} \tag{2}$$

where k_x, k_y, and k_z are wave numbers associated with the x, y, and z directions, $k = \omega/c$, $\omega = 2\pi f$, and f is the frequency. Inserting this relationship into the wave equation results in the following expression for the sound pressure p:

$$p(x,y,z,t) = A\cos(k_x x)\cos(k_y y)\cos(k_z z)\, e^{-iwt} \tag{3}$$

where the following relationship must apply in order to satisfy the wave Equation (1):

$$\frac{\omega}{c} = k = (k_x^2 + k_y^2 + k_z^2)^{1/2} \tag{4}$$

When the sound propagation is in an enclosed space, such as a room, it is limited in extent by the presence of the walls. The boundary condition that must be applied to Equation (3) is that the particle velocity is zero at the walls (which are assumed to be rigid). With the room dimensions L_x, L_y, and L_z, it can be shown that for the particle velocity to be zero at $x = L_x$, then $k_x L_x = l\pi$ where l is an integer 0, 1, 2, 3... etc. Similarly, $k_y L_y = m\pi$, and $k_z L_z = n\pi$, where m and n are integers 0, 1, 2, 3... etc., and L_y and L_z are the (y, z) dimensions of the room. Thus Equation (3) becomes:

$$p_{lmn}(x,y,z,t) = A_{lmn}\cos\left(\frac{l\pi x}{L_x}\right)\cos\left(\frac{m\pi y}{L_y}\right)\cos\left(\frac{n\pi z}{L_z}\right)e^{-i\omega t} \tag{5}$$

The sound field in the room therefore consists of a series of natural resonant frequencies, or modes, at frequencies determined by the room dimensions and the integers (l, m, n). The frequency f_N of the natural modes is determined from Equation (4) as:

$$f_N = f_{l,m,n} = \frac{c}{2}\left[\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2\right]^{1/2} \quad (6)$$

The fundamental modes of the room with two of the integers l, m, n equal to zero, e.g., (1, 0, 0), (0, 1, 0), are called axial modes, which are one-dimensional (1D) modes with reflections from two parallel walls. These modes will tend to be the strongest of all the modes as they involve reflections and absorption from only two walls. Tangential, 2D modes have just one of the integers as zero, e.g., (1, 1, 0), (0, 1, 1), etc., with reflections from four walls. The 3D oblique modes have none of the integers as zero, e.g., (1, 1, 1), (2, 2, 1), with reflections from all six walls and will tend to be the weakest of the three classes. For a typical residential room of volume 1,440 cu ft, with dimensions 15 ft x 12 ft x 8 ft, the three fundamental frequencies of the axial modes are 38 hertz (Hz), 47 Hz, and 71 Hz, with other higher-order axial modes at the harmonics 76 Hz, 94 Hz, and 142 Hz. The number of modes increases with increasing frequency as the axial modes combine with the tangential and oblique modes for higher-order values of l, m, n. With this increase in modes, the sound pressure at any given point in the room will become more regular with increasing frequency.

The number of modes at any given frequency can be determined from Equation (6), but this is a difficult process for calculating all the tangential and oblique classes of modes. Since the modal frequencies form a well-defined 3D sequence with constant intervals of $c/2L_X$, $c/2L_Y$, $c/2L_Z$ on the (x, y, z) room axes, it is possible to count the cumulative total number of modes as a function of frequency. With this simplified approach, the average number, N, of modes of all types with frequencies less than f is (Morse, 1948):

$$N = \frac{4\pi V f^3}{3c^3} + \frac{\pi S f^3}{4c^2} + \frac{Lf}{8c} \quad (7)$$

where $V = L_xL_yL_z$, $S = 2(L_xL_y + L_xL_z + L_yL_z)$, $L = 4(L_x + L_y + L_z)$. In this equation, the first term represents the oblique modes, the second term the tangential modes, and the third term the axial modes. As frequency is increased, the number of oblique modes rapidly becomes the dominant factor.

Since noise measurements are usually conducted with data in one-third octave bands, it is perhaps more relevant to know how many modes there are in each frequency band. This can be determined by differentiating Equation (7) as follows:

$$dN = \left(\frac{4\pi V f^2}{c^3} + \frac{\pi S f}{2c^2} + \frac{L}{8c}\right) df \quad (8)$$

For a one-third octave band centered on frequency, f_c, $df = 0.23f_c$. With this substitution, the number of modes, dN, in a one-third octave band for small, medium, and large rooms—of volume 960 cu ft, 1,440 cu ft, and 2,560 cu ft, respectively—is shown in Table 1.

Table 1. Number of Modes in Small, Medium, and Large Rooms

	Small	Medium	Large
Dimensions (ft)	12x10x8	15x12x8	20x16x8
Volume (ft^3)	960	1440	2560

Band Center Frequency	Bandwidth (Hz)	Number of Modes in 1/3 Octave Band		
		Small	Medium	Large
100	23	4	6	9
125	29	7	10	16
160	37	13	18	31
200	46	23	33	56
250	58	41	60	103
315	72	78	114	197
400	92	152	223	387

Table 1 shows that, for a small room, there are only four modes in the 100-Hz frequency band, which has a width of 23 Hz; and a total of nine modes for a large room. The modal density, the number of modes per Hz, exceeds unity at 315 Hz, 250 Hz, and 200 Hz for the small, medium, and large rooms, respectively. With few modes per one-third octave band, the spacing between individual modes becomes large, and the variation of sound pressure with both frequency and measurement point can be significant. The data in Table 1 is presented graphically in Figure 1, showing the rapid increase in modes with increasing frequency.

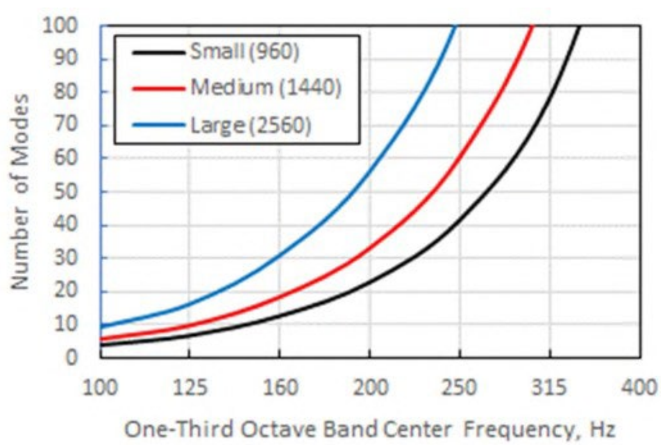


Figure 1. The Number of Modes in One-Third Octave Bands for Small, Medium, and Large Rooms (Volumes in Cu Ft)

To understand the interaction of a noise source with the room modes, it is necessary to return to the general wave equation of Equation (1) with a noise source included. Equation (5) can be written in a simplified form as:

$$p_N(x,y,z,t) = A_N \psi_N(x,y,z) e^{-i\omega_N t} \tag{9}$$

where ψ_N is a function that defines the sound pressure spatial distribution of the N^{th} mode, for the trio of integers (l, m, n). The total sound pressure p at any point in the room is then given by the sum of the pressures in all the modes, namely:

$$p_N(x,y,z,t) = \sum_N p_N = \sum_N A_N \psi_N(x,y,z) e^{-i\omega_N t}$$

If the position of the source is (x_S, y_S, z_S) then in a similar manner to that of Equation (9), the source strength spatial distribution can be represented as:

$$q_N(x_S, y_S, z_S) = Q_0 \psi_N(S)$$

Summing over all modes:

$$q(S) = \sum_N q_N(S) = \sum_N Q_0 \psi_N\,(S)$$

where S represents the coordinates (x_S, y_S, z_S) of the noise source.

With this substitution, the expression for the sound pressure at a point P produced by a source at a point S can be obtained (Morse, 1948):

$$p = \rho c^2 \sum_N \frac{K_N \omega \psi_N(S) \psi_N(P)}{(2k_N\omega_N)^2 + (\omega_N^2 - \omega^2)^2} \tag{10}$$

where K_N is a constant for the N^{th} mode, $\psi_N(P)$ represents the value of the spatial distribution ψ of the N^{th} mode at the coordinates of the point where the sound pressure is measured, and k_N is the damping factor for the N^{th} mode. The measured sound level will therefore vary with position according to the square of the expression in Equation (10). If the level is measured using a 3D scan over the main body of the room, excluding areas close to the walls, then the average value of $\psi_N(P)$, calculated by integrating p^2 over the volume of the room, is 1, effectively averaging out the variability. A 2D scan conducted in the (x, y) plane parallel to the wall at z = 0 eliminates the variation in one dimension but is subject to a constant bias at frequencies where the distance from the wall is comparable to one-fourth wavelength of the sound wave.

The function $\psi_N(S)$ represents the spatial distribution ψ of the N^{th} mode at the coordinates of the point where the source of sound is located, forming a coupling coefficient of the source with the sound field. If the source is in a corner, then $\psi_N(S) = 1$. If the source is placed near a room surface, the coupling to the room modes will be poor at the frequency where the distance to a wall is one-fourth the wavelength of the sound wave. There will be additional discussion on this later in this section.

The denominator of the expression in Equation (10) contains the information on the frequency response of the sound pressure for given source and measurement locations. The factor k_N represents the damping factor at the frequency of the N^{th} mode, comprising the absorption at the walls and from the furnishings of the room. If the damping is low, then the bandwidth of the mode (the frequency range between the -3 dB points on the frequency response) is small, as shown by the solid black curve in Figure 2 at the frequency f_2. Increasing the damping results in an increase in bandwidth, as shown by the dashed black line in the figure. The higher the absorption in the room, the broader the bandwidth. (For convenience, the levels shown for the peaks of the curves in Figure 2 have been normalized to 0 dB. In fact, increasing the damping will reduce the maximum level at the modal frequency).

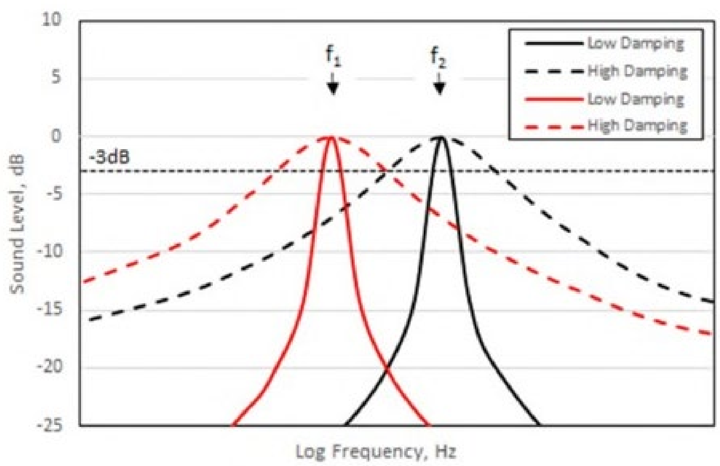


Figure 2. Illustration of the Effect of Damping on Modal Bandwidth

Figure 2 also shows the frequency response of a second adjacent mode at f_1 Hz as indicated by the solid red curve. At low frequencies where there are few modes, there is little overlap of the lightly damped modes—the two solid curves in Figure 2. As a result, the sound level will vary considerably with frequency and position in the room. Increasing the damping increases the amount of overlap between the modes, as shown by the two dashed curves in Figure 2, resulting in a smoother frequency response. Because a typically furnished room has reasonably high absorption, individual modes do not generally dominate the spectrum at low frequencies where the modal density is low.

2.2.2 Sound Fields at Medium and High Frequencies

At higher frequencies, Equation (7) shows that there are many more modes and hence greater overlap and fewer deep troughs between them, especially if the damping from room absorption is high. In this frequency region, there is little variation in sound level with position. In large rooms with moderate absorption, the sound field can be considered diffuse—a condition in which the sound energy is uniformly distributed throughout the room, and there is an equal probability of sound propagation in all directions. Under these conditions, the sound intensity, and hence sound level, will be essentially the same at all points in the room, except near the noise source and the walls. Calculations in room acoustics usually assume diffuse conditions for simplicity, but this ideal condition is rarely achieved in smaller residential rooms. It is usual to refer to sound fields in these rooms at medium and high frequencies as *reverberant*.

The frequency at which a sound field can be considered reverberant is arbitrary as the transition from modal to reverberant is a continuous process with increasing frequency. A cutoff frequency, f_S, for the transition has been proposed (Schroeder, 1962) as the frequency at which the modal bandwidth is three times the average spacing between adjacent modes. Schroeder provides an estimate for this frequency as:

$$f_S = 12000\sqrt{\frac{T_{6O}}{V}} = 12000\sqrt{\frac{0.049}{A}} \tag{11}$$

where T_{6O} is the reverberation time of the room in seconds, V is its volume in cu ft, and A is the acoustic absorption in ft^2. For a typical medium-sized room with a volume of 1,440 cu ft, and a reverberation time of 0.45 seconds, the cutoff frequency is 212 Hz. At frequencies greater than this, the sound field can be assumed to be reverberant and can be analyzed using statistical methods. The cutoff frequencies for the small and large rooms included in Table 1 are 260 Hz and 160 Hz, respectively. Assuming that the transition occurs when the modal bandwidth is equal to three times the average, modal spacing may be conservative for practical purposes; so the statistical calculation and measurement methods can usually be used at frequencies lower than f_S, but with caution.

The sound intensity at any point in the room is the sound power flowing normally through a unit area. In a free progressive plane wave, the intensity, I, is (Beranek 1986):

$$I = p^2/\rho c$$

A completely diffuse sound field consists of an infinite number of plane waves passing through a unit area in all directions. Considering the energy flowing through the unit area in one direction only, and averaging over all angles of incidence from the intensity, I_r, of the sound field is given by the expression (Beranek, 1986):

$$I_r = p_r^2/4\rho c \tag{12}$$

where p_r is the sound pressure in the reverberant field. The number "4" in the denominator implies that the interior sound field is perfectly diffuse, i.e., an equal probability of sound propagating in all directions. Note that with this definition, the intensity in a diffuse sound field must technically be zero. The quantity I_r in Equation (12) is therefore the "one-way" intensity, representing the flow of sound energy in one direction through a unit area anywhere, in any direction, in the room.

A noise source in the room will produce a sound level such that, under steady-state conditions, the sound power generated is equal to that absorbed. For a source of sound power W,

$$W = I_r A = \frac{p_r^2}{4\rho c} A$$

or

$$p_r^2 = 4\rho c W/A \tag{13}$$

where A is the total absorption in the room (related to the factor k_N in Equation (10)). Equation (13) represents the sound pressure in the diffuse sound field. Close to the source, however, the sound level will be dominated by the direct sound radiated by the source. At a distance r from an omnidirectional source, the intensity, I_d, of this direct sound is related to the sound power by the expression:

$$I_d = W/4\pi r^2 = p_d^2/\rho c \tag{14}$$

where p_d is the sound pressure of the direct radiation from the source. Alternatively,

$$p_d^2 = \rho c W/4\pi r^2 \tag{15}$$

Summing the expressions for sound pressure in Equations (14) and (15) gives an expression for the total sound pressure p^2 at any point in the room from the direct and diffuse sound field contributions, namely:

$$p^2 = p_d^2 + p_r^2 = \rho c W\left(\frac{1}{4\pi r^2} + \frac{4}{A}\right) \tag{16}$$

This relationship is presented in Figure 3 as a function of distance from the source for different values of room absorption. The dashed line in this figure represents the sound level of the direct radiation from the source as given by the inverse-square relationship of Equation (15).

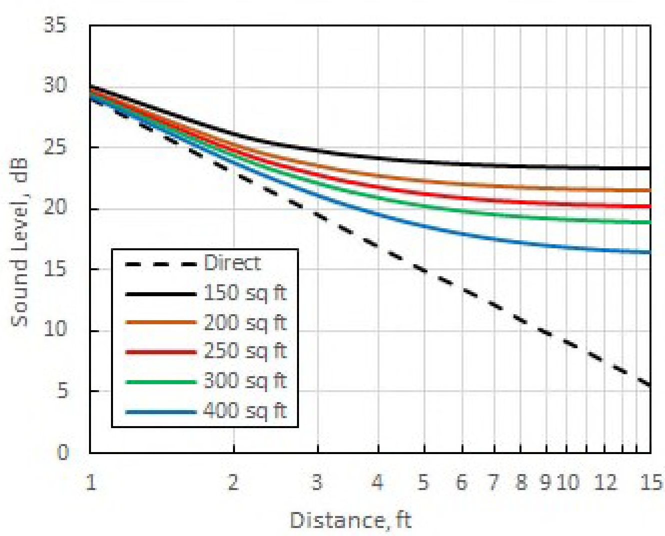


Figure 3. Sound Level versus Distance from a Noise Source in an Enclosed Space

The different curves in the figure show the trend towards an asymptotic level with increasing distance for different values of room absorption ranging from 150 to 400 sq ft. This asymptotic level is equal to the level of the reverberant sound—the higher the absorption, the lower the level. For a typical room with an absorption of 250 sq ft, the sound level approaches within 1 dB of the asymptotic value at 4 to 5 ft from the noise source. Therefore, for an accurate measure of the reverberant sound level in a room, the measurement should not be conducted closer to the noise source than this critical distance. Moreover, to fully characterize the reverberant sound field, the sound level should be averaged by means of a 3D scan. Hopkins (2011) recommends that such a scan should be performed from a standing position to avoid noise from operator footsteps.

The relationships shown in Figure 3 are based on the assumption of a diffuse sound field. In practice, and certainly in small residential rooms, such an ideal sound field cannot be realized because the presence of significant localized absorption does not allow for an equal distribution of sound energy. Schultz (1980 and 1985) has argued that the diffuse field theory of sound propagation indoors does not work for typical furnished rooms in dwellings and offices, and presents empirical data from several sources to demonstrate that the sound level decreases according to a 10log(distance) relationship, where the level decrease at a rate of 3 dB per doubling of distance over the entire room. In other words, there is no transition from direct to reverberant sound field. Schultz presents the data with such a relationship superimposed, but it is apparent in the data for small rooms typical of a furnished residence that there is a transition from a direct to a reverberant sound field at distances from 3 to 6 ft; the level is fairly constant at larger distances, consistent with the relationship of Equation (16). Although Schultz's conclusions may be appropriate for larger industrial and commercial rooms, the diffuse sound field theory may be appropriate for residential rooms. Additional empirical data is needed to validate this assumption.

2.2.3 Sound Fields Near Room Boundaries

The discussion of sound fields in rooms has so far not considered the behavior near the room boundaries where the presence of reflected sound energy can give rise to interference patterns similar, but not identical to, those experienced in measurements near the exterior facades of buildings exposed to loudspeaker noise (Sharp et al., 2018). The difference between the two is that the former patterns are interference from a reverberant sound field, whereas the latter are from a single incident plane sound wave. Understanding the degree and extent of these patterns is important in selecting appropriate procedures for defining interior levels as part of an I-O method for measuring noise reduction.

The theory for describing the sound field near the boundary of a room with a diffuse sound field has been developed by Waterhouse (1953) and expanded to show noise contours in Waterhouse (1955). In these documents, the mean-square sound pressure at a distance x from a reflecting wall produced by a single plane wave incident at an angle Θ is given by the expression:

$$p^2(x, \theta) = 2p_i^2(1 + \cos(2kx\, cos\, \theta)) \qquad (17)$$

where p_i^2 is the mean square pressure of the incident plane wave. This relationship predicts an increase in sound level of 6 dB at the surface of the wall. In a diffuse sound field, all angles of incidence are present, and so the sound pressure in Equation (17) must be integrated over angle, resulting in the following expression for the total mean-square sound pressure:

$$p^2(x) = p_r^2\left(1 + \frac{\sin 2kx}{2kx}\right) = p_r^2(1 + j_0(2kx)) \qquad (18)$$

where p_r^2 is the mean-square pressure of the diffuse sound field in the main body of the room, and $j_0(x)$ is the spherical Bessel function. In this case, the increase in sound level at the wall surface over that in the main body of the room is only 3 dB. An analysis for the increase in sound pressure near the edge of a room where two walls meet results in the expression (Waterhouse, 1955):

$$p^2(r) = p_r^2[1 + j_0(2kx) + j_0(2ky) + j_0(2kr)] \quad (19)$$

where $r = \sqrt{x^2 + y^2}$ is the diagonal distance of the (x, y) location from the edge of the room. For locations near a corner, a similar expression can be developed in three dimensions (Waterhouse, 1955), such that the equivalent expression to that of Equation (19) has seven terms. The increase in sound level near a wall, an edge, and a corner are plotted in Figure 4 as a function of x/λ for a wall, or r/λ for an edge or corner, showing an increase of 3, 6, and 9 dB, respectively, for x or $r = 0$ at the surface of the wall or in the edge or corner.

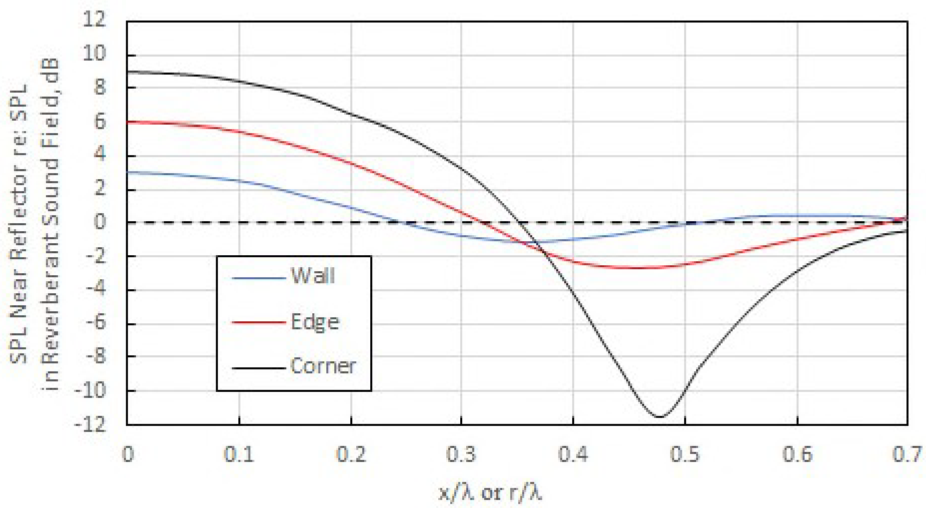


Figure 4. Increase in Sound Level Near a Wall, Edge, and Corner of a Room with a Diffuse Sound Field (Data from Waterhouse, 1955)

The curves in Figure 4 are calculated for a single frequency. However, for a typical bandwidth of a one-third octave or one octave, the interference curve is little different from that for a single frequency, the only exception being that the minima are less pronounced.

The increase in level close to a wall decreases with distance from the wall until it is zero at 0.25λ (the blue line in Figure 4). For the level to be within 0.5 dB of the reverberant level in the room, the measurement distance must be no less than 0.22λ from the wall. At greater distances, the increase is generally less than 1 dB. The corresponding distances for edges and corners for the measurement to be within 0.5 dB are 0.64λ and 0.7λ, respectively. Figure 5 shows the measurement distances required for the 0.5 dB criteria to be met as a function of frequency.

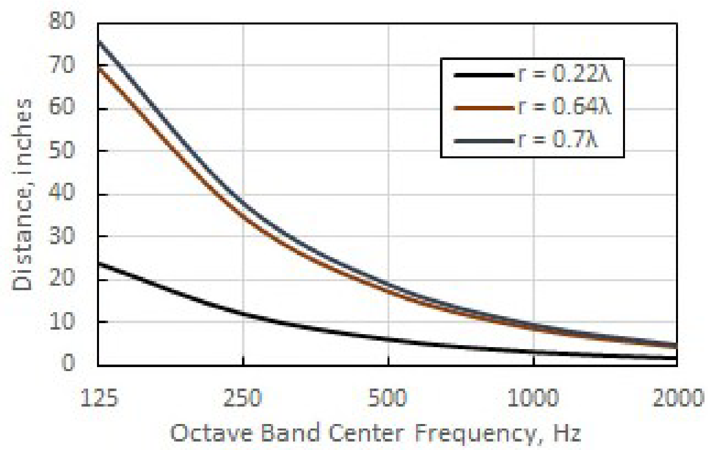


Figure 5. Minimum Distances from a Wall Surface for Sound Level Measurements in a Room to be Within 0.5 dB of the Reverberant Level

Thus, for a measurement of the reverberant level in a room at 125 Hz to be within 0.5 dB of the reverberant level in the room, the microphone should not be closer than 24 in. from a wall surface, or about 70 in. from a room edge or corner. For comparison, the American Society for Testing and Materials (ASTM) (2019) and the International Organization of Standardization (ISO, 2016a) guidelines recommend a minimum distance of 0.5 m (20 in.) from any room surface.

If a distance of 24 in. is maintained from any surface for a scan, the distances from an edge or corner would be 34 in. and 41 in., respectively, so the 0.5 dB criterion would be met at 250 Hz. Clearly, the further from a surface the better, but increasing the distance has to be balanced by considerations for room size, and the extent of the direct sound field from the noise source as shown in Figure 3.

2.2.4 Noise Source Output

The presence of a wall adjacent to a noise source will change the sound power output of the source due to the change in radiation impedance caused by reflections from the wall reacting back onto the source (Waterhouse, 1958). This change in output is directly related to the interference patterns described in the relationships of Equations (18) and (19) caused by reflections from the wall or room edge (and a similar relationship for a room corner). To generate the highest sound levels, the optimum location for the noise source is in a room corner, where the output is theoretically 9 dB more than if it is placed at a random position in the room. The location to avoid is at a distance of $r/\lambda = 0.5$ from the corner where the output is at a minimum. The data in Figure 4 shows that the output of the loudspeaker is diminished by more than 1 dB in the region where the distance from the corner is between 0.36λ and 0.65λ. At a distance of 3 ft, this range in distance corresponds to a frequency range of 135 to 250 Hz. For a distance of 5 ft, the range is 80 to 145 Hz.

The guidelines for noise source placement in ASTM (2019b) recommend that a loudspeaker should be at least 1 m (3.28 ft) from the apex of the corner. In addition, the diffusion of the sound field in the room can be increased by facing the loudspeaker towards the corner. Furthermore, the loudspeaker should be placed in or near a corner of the test room farthest from the exterior wall(s) to be measured so as to minimize the variation of sound level over the wall surfaces (ASTM, 2019b). Based on the above analysis, the loudspeaker should preferably be no closer than 5 ft from the corner for measurements at 125 Hz.

2.3 SOUND RADIATION FROM FACADES

A critical part of the I-O test procedure is the measurement of the sound level outside the building, specifically, the exact location where this level is to be measured. The procedure in most acoustical engineering projects designed to characterize source noise emissions is to conduct the measurements in the far-field where the noise source can essentially be considered as a point source (a source concentrated at a single point), and the levels can be easily extrapolated to larger distances. In the I-O test procedure, however, the sound levels generated by radiation from the building facade will be relatively low, and consideration must be given to possible contamination from exterior background noise. As a result, the measurements must be taken close to the facade where the radiation from the facade can be considered as a plane wave with little variation with distance. The challenge is determining how close should this be for the assumption to be valid.

There is extensive published literature on the radiation of sound from circular and rectangular pistons and panels with flexural vibration, but the main objective of this work has been to estimate the radiation impedance, and on the far-field sound pressures generated by these sources. Few have examined the near-field sound pressures. Bies (1976), in concluding that the task of defining where the far-field starts has hardly been considered, divides the radiation from an extended source into three regions, namely:

- Hydrodynamic near-field, extending out to about one wavelength, where particle velocity and pressure are not in phase, and fluid motion is not associated with wave propagation.

- Geometric near-field, extending out for a few wavelengths, where constructive and destructive interference effects can occur. These can be particularly evident with pure tones, but tend to diminish with increased bandwidths. In this region, the radiation is in the form of a plane wave.

- Far-field, where the sound pressure decreases inversely with increasing distance (the inverse- square law).

In the geometric near-field, the particle velocity and pressure are in phase, and it can be assumed that the sound propagation is normal to the measurement surface, and that the radiated sound power can be calculated from measurements (Bies, 1976). As the propagation is in the form of a plane wave where the sound pressure does not decrease with distance, this is the region most suitable for the measurements of I-O noise reduction. Bies examines the case of a rigid piston whose dimensions are much greater than a wavelength and suggests that the maximum extent of the geometrical near-field can be defined as:

$$x < \frac{b^2}{\lambda}$$

where b is the characteristic dimension of the piston in meters. Applying this expression to a facade that is 8 ft high, then at a frequency of 125 Hz, the maximum distance at which the radiation can be considered a plane wave is 2.2 ft. The maximum distance for a window of height 4 ft is 0.6 ft. According to this theory, the distance increases with frequency.

Freedman (1960) examined the sound field generated by radiation from a rectangular piston vibrating within an infinite baffle, and developed laws of behavior of the sound field as a function of distance. He also suggests a method for predicting far-field sound levels based on measurements in the geometric near-field. Freedman concludes that, if the piston dimensions are sufficiently large, then at distances less than twice the square of the piston width, the sound pressure exhibits fluctuations about a level corresponding to plane wave. Specifically, the condition can be expressed as:

$$x < \frac{2b^2}{\lambda}$$

where b is the half-width of the piston. Applying this relationship to a facade of height 8 ft, then at a frequency of 125 Hz, the maximum distance at which the radiation can be considered a plane wave is 3.7 ft. The maximum distance for a window of height 4 ft is 0.9 ft. According to this theory, the distance increases with frequency.

Ocheltree (1989) also presents a method for calculation of the sound field from a rigid piston source surrounded by a plane rigid baffle. Due to rectangular pistons, the fields cannot be characterized as easily since rectangular sources have two descriptive dimensions, and their fields lack the axial symmetry associated with circular sources. Thus, the field from a rectangular source is dependent on the ratio of the two sides of the source in addition to their size relative to a wavelength. Transition from near-field to far-field occurs at distances where:

$$x < \frac{b^2}{4\lambda}$$

where b is the length of the side of the source. Applying this equation to a facade of height 8 ft, then at a frequency of 125 Hz, the maximum distance at which the radiation can be considered a plane wave is 1.8 ft. The maximum distance for a window of height 4 ft is 0.5 ft.

A simpler relationship was developed by Rathe (1969), who considered the source to be a rectangular panel consisting of an infinite number of uncorrelated point noise sources. By summing the contribution at a given point from all the individual point sources, Rathe concluded that the maximum distance for which the radiation could be considered a plane wave was given by the expression:

$$x < \frac{b}{\pi}$$

where b is the smallest dimension of the rectangular source. Applying this expression to a facade of height 8 ft, then the maximum distance at which the radiation can be considered a plane wave is 2.6 ft. The maximum distance for a window of height 4 ft is 1.3 ft. The distance is frequency independent due to the assumption that the intensity contributions from all the point sources are additive.

A summary of the different estimates of the extent of the near-field where the sound propagation is in the form of a plane wave is given in Table 2.

Table 2. Estimates of the Extent of the Near-Field of a Radiating Panel

	Maximum Distance of Near Field @ 125 Hz	
Reference	Wall (8 ft)	Window (4 ft)
Freedman (1960)	3.7	0.9
Ocheltree (1989)	1.8	0.5
Bies (1976)	2.2	0.6
Rathe (1969)	2.6	1.3
Range	2–3	0.5–1

2.4 CALCULATION OF NOISE REDUCTION

2.4.1 Outdoor-Indoor Noise Reduction

The standard SAE 6973 test procedure for measuring the noise reduction of a building facade exposed to aircraft noise requires a loudspeaker placed outside the building, with sound level measurements at or near the external facade and inside the room behind the facade. The SAE procedure is designed to simulate the noise exposure, and the noise reduction, experienced by the building occupants during an aircraft flyover. The O-I noise reduction is defined as the difference between the exterior incident sound level and the average level inside the room. Assuming that the incident sound is a free progressive plane wave, the intensity, I_i, of the sound incident to the exterior facade, can be written as (Beranek, 1996):

$$I_i = p_i^2/\rho c \tag{20}$$

where p_i is the exterior incident root-mean-square sound pressure, ρ is the density of the air, and c is the speed of sound in air. The quantity ρc is the acoustic impedance of air. The sound power, W_t, which will be transmitted into the receiving room by the wall is:

$$W_t = \tau_\theta \, I_i S cos(\theta) = \tau_\theta p_i^2 S cos\theta/\rho c \tag{21}$$

where τ_θ is the sound transmission coefficient of the wall at the source frequency, at an angle of incidence θ, and S is the surface area of the facade exposed to the noise source.

Under steady-state conditions, a sound level will be established in the room such that the sound power absorbed is equal to the sound power transmitted into the room. If the sound field is perfectly diffuse, then:

$$W_t = I_r A = p_r^2 A/4\rho c \tag{22}$$

where I_r and p_r are the intensity and root-mean-square sound pressure, respectively, of the reverberant sound field in the room, and A is the total absorption (Beranek, 1996).

The O-I noise reduction, NR_{OI}, of the facade is defined as the difference between the incident exterior sound level, L_i, and the interior sound level, L_r:

$$NR_{OI} = L_i - L_r = 10\log(p_i^2/p_r^2)$$

Rearranging Equations (21) and (22), the O-I noise reduction, $NR_{OI\theta}$ of the facade for sound incident at an angle θ is:

$$NR_{OI\theta} = TL_\theta - 10\log\left(\frac{Scos\theta}{A}\right) - 6, dB \quad (23)$$

where $TL_\theta = 10\log(1/\tau_\theta)$ is the sound transmission loss of the facade at angle of incidence θ.

2.4.2 Indoor-Outdoor Noise Reduction

The I-O method for measuring noise reduction involves using a loudspeaker to establish a sound field inside the room to be tested and measuring the sound levels inside and outside the room—essentially the reverse of the O-I method. If it is assumed that the interior sound field is perfectly diffuse, then the steady-state sound pressure in the room is given by Equation (22):

$$p_r^2 = 4\rho c W/A$$

where W is the sound power output of the loudspeaker. The intensity, I_r, of the sound field in the room generated by the loudspeaker is given by the expression:

$$I_r = p_r^2/4\rho c$$

The sound power, W_t, transmitted through the room facade is:

$$W_t = \tau I_r S = \tau p_r^2 S/4\rho c$$

where S is the surface area of the wall, and τ is the sound transmission loss of the facade for random incidence.

The sound field at the exterior of the room will approximate a series of plane progressive waves at a distance close to the facade (see Section 2.3). At this distance, the sound power, W_t, is given by:

$$W_t = \tau l_r S = \tau p_r^2 S/4\rho c$$

The difference between the level of the sound incident on the wall of the test room and the level close to the exterior facade, namely:

$$L_r - L_t = 10\log(p_r^2/p_t^2) = TL + 6, dB \quad (24)$$

where L_r is the average level of the interior reverberant sound field, and L_t is the sound level of the plane wave transmitted through and radiated by the facade.

The expressions for O-I noise reduction in Equations (23) and the level difference in Equation (24) both include the transmission loss of the test facade. However, the transmission loss, *TL*, of the facade for random incidence in Equation (24) for the indoor-outdoor transmission is not necessarily the same as the transmission loss, TL_Θ, in Equation (23) for incident sound at a single angle Θ. Normal practice is for the O-I noise reduction to be measured with the loudspeaker positioned for the sound to be incident at or close to 45 degrees (SAE, 2021). Field measurements have shown that the measured noise reduction is not sensitive to angle of incidence (Sharp, 2019). This does not necessarily mean that transmission loss is not a function of angle of incidence, but it does imply that it is not a strong function. As a result, the numerical values of TL and TL_θ may be very close, such that $TL = TL_\Theta + \delta TL$. With this assumption, combining Equations (23) and (24) results in the expression:

$$NR_{OI} = (L_r - L_t) - 10\log(S/A) - 12 - \delta TL$$

For the purposes of comparing values of I-O noise reduction with those measured using the standard O-I measurement method, the I-O noise reduction, NR_{IO}, will be defined as follows:

$$NR_{IO} = L_r - L_t - 10\log(S/A) - K \quad (25)$$

where $K = 12 + \delta TL$.

Note that the I-O method must incorporate a measure of the room absorption for the two test methods to be equivalent.

In most practical residential situations, the sound field is never perfectly diffuse as described in Equation (20), due to the abundant presence of absorbing surfaces and furniture. As a result, the numerical factor "12" in Equation (25) may not be appropriate. The factor *K*, which needs to be determined empirically through field measurements, will effectively incorporate this and any other unknown factors.

2.5 CONCLUSIONS FROM LITERATURE REVIEW AND ANALYSIS

The literature review and analyses were designed to evaluate the many parameters involved in an I-O test procedure for the measurement of noise reduction, and to select those most appropriate. The conclusions from the analyses are as follows:

- The sound field in a room is dominated by the energy in the natural room modes of the room at low frequencies, resulting in a sound pressure that varies considerably both from point to point and with changing frequency. As the frequency is increased, the number of modes increases and begin to overlap such that the sound pressure is more constant with position and frequency, and is considered reverberant.

- The frequency at which the sound field transitions from modal to reverberant depends on the room dimensions and the amount of absorption—the larger and more absorptive the room, the lower the transitional frequency. For a typical medium-sized furnished room with a volume of 1,440 cu ft and a reverberation time of 0.45 seconds, the transitional frequency is 212 Hz.

- At frequencies above the transitional frequency, it is reasonable to model and measure the sound field using statistical methods, assuming that the fields are diffuse. At lower frequencies, these methods should be used with caution.

- To minimize interference effects that reduce the loudspeaker output, the loudspeaker should be at least 3 ft, and preferably 5 ft, from, and facing, the corner. Furthermore, the loudspeaker should be placed in or near a corner of the test room farthest from the exterior wall(s) to be measured so as to minimize the variation of sound level over the wall surfaces.

- For an accurate measure of the reverberant sound level in a room, measurements should not be conducted closer than 5 ft to the noise source. Moreover, to fully characterize the reverberant sound field, the sound level should be averaged by means of a 3D scan.

- For a measurement of the reverberant level in a room at 125 Hz to be within 0.5 dB of the true value, the microphone should not be closer than 24 in. from a wall surface, or about 70 in. from a room edge or corner. If a distance of 24 in. is maintained from any surface, the distances from an edge or corner would be 34 in. and 41 in. respectively, so the 0.5 dB criterion would be observed at 250 Hz.

- The near-field of the sound transmitted and radiated to the exterior extends to a distance that depends on the element dimensions and the frequency. At a frequency of 125 Hz, the near-field for an 8-ft facade extends to between 2 and 3 ft, and for a 4-ft window it extends from 0.5 to 1 ft.

- To compare values of I-O noise reduction with those measured using the standard O-I measurement method, the I-O noise reduction, NR_{IO}, is defined as follows:

$$NR_{IO} = L_r - L_t - 10\,log(S/A) - K$$

  where the value of $K = 12 + \delta TL$ is to be empirically determined.

The field measurements described in the following Sections 3 and 4 will determine if the value of the factor K is a constant that can be applied in the measurement of I-O noise reduction in typical building structures.

3. FIELD EVALUATION OF MEASUREMENT PARAMETERS

Two sets of parameter tests were designed to validate the findings of the literature review and analysis and provide the necessary details to define an indoor-to-outdoor I-O test procedure. The specific objectives of the tests were as follows:

a) Examine interior sound field near the wall surface.
b) Examine exterior sound field near the wall surface.
c) Determine the extent of direct and reverberant interior sound fields.
d) Measure room absorption with a reference sound source (RSS).
e) Evaluate the effect of loudspeaker position.
f) Determine the value of the constant *K* for the sound field in a typical furnished room.

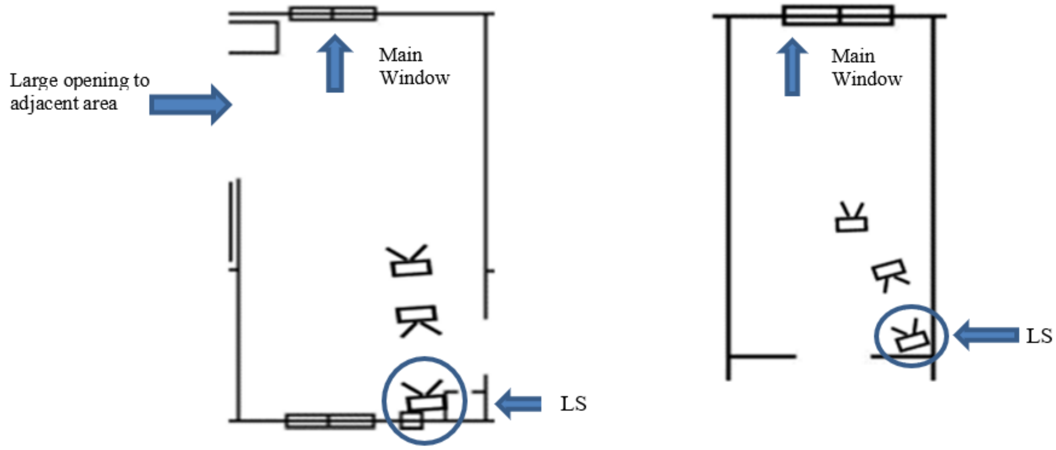
3.1 PARAMETER TEST ROOM DETAILS

The parameter tests were conducted in two rooms in each of two buildings. The details of the rooms are presented in this section.

3.1.1 Parameter Test House 1

The first series of parameter tests were conducted in two rooms of an apartment on the second floor of a two-story building. The larger of the two rooms, shown in Figure 6(a), was 20 ft x 17 ft x 10 ft and lightly furnished with a partial carpet. The main feature of the test facade was a 3½-ft x 3¾-ft window on one wall, the remaining area of which was partly furnished with a bookcase and cabinets. The room was connected to an adjoining space by a large opening. The loudspeaker was placed in, or adjacent to, a corner on the opposite side of the room that was between the wall and a cabinet.

The smaller of the two rooms, shown in Figure 6(b), was 13½ ft x 7½ ft x 10 ft, was furnished with a rug, and had a 3½-in. x 3¾-in. window that was the main feature of the test wall. This small room had an opening to an adjoining space with a door that was closed during the tests. The loudspeaker was placed in, or adjacent to, a corner on the opposite side of the room to the test wall.



(a) Large Room (b) Small Room

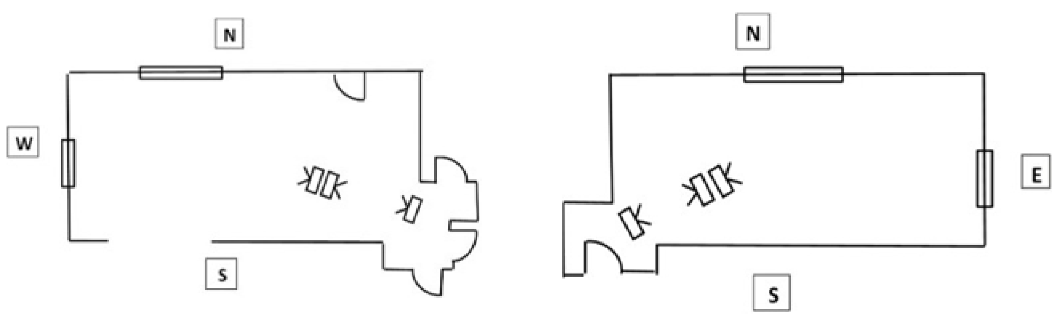
Figure 6. Floorplan of Rooms for Parametric Tests 1

3.1.2 Parameter Test House 2

The second series of parameter tests were conducted in two rooms, a den and a bedroom, of a single-story house with an exterior vinyl siding facade, as shown in Figure 7. The den, shown in Figure 7(a), was 15½ ft x 11½ ft x 8 ft. The room was connected to a kitchen by a large opening. The floor had wall-to-wall carpet.

The second test room was a bedroom, 12 ft x 9½ ft x 8 ft, also with two exterior walls, each with a 2½-ft x 4⅓-ft window, as shown in Figure 7(b). The floor had a rug over a hardwood floor.

In each room, the loudspeaker was placed in, or adjacent to, a corner that formed the entrance to the rooms, on the far side of the room from the two exterior walls.



(a) Den (b) Bedroom

Figure 7. Floorplan of Rooms for Parametric Tests 2

3.2 PARAMETER TEST MEASUREMENTS

I-O noise reduction levels were measured for a range of test parameters to identify the most reliable method for simulating the measured O-I noise reduction. The noise source for the measurements was a Mackie SRM350 loudspeaker with an input of pink noise. The output of the loudspeaker was monitored for all tests by means of a microphone located at a distance of 1 ft on axis. The measurement parameters were as follows:

- Loudspeaker Positions (see Figures 6 and 7):
  a) In the room corner farthest from the test wall, floor level, facing out from the corner.
  b) 5 ft (3 ft for Tests 1) from corner, floor level, facing in toward the corner, angled upwards.
  c) 5 ft (3 ft for Tests 1) from corner, floor level, facing test wall.

- Interior sound level measurements for all loudspeaker positions:
  a) 2D scan over the interior of opposing wall/window area at distances of 1, 6, 12, 24 in. for 20 seconds.
  b) 2D scan over window and wall separately at distance of 1 inch for 20 seconds.
  c) 3D volume scan, maintaining a distance of 2 ft from all room surfaces, and 5 ft from the loudspeaker for 20 seconds. This measurement was repeated three times.

The 2D wall scans were performed over the central area of each wall (including the windows and doors), not including areas within 2 ft of the floor, ceiling, or edges of the room.

Exterior sound level measurements while maintaining the same interior sound level as measured by monitoring microphone:

- 2D scan over entire wall/window surface at 6, 12, and 24 in. (over the same area as interior measurement) for 20 seconds.

O-I Measurement of noise reduction:

- Following ARP 6973 guidelines for loudspeaker distance, height, and angle of incidence.

RSS, Acculab RSS 101, positioned at loudspeaker position (a) at a height of 4 ft above floor level:

- Measurement of sound level along a horizontal, diagonal line at 2, 4, 8, 12, and 16 ft from the RSS, for 10 seconds at each position with microphone at 4 ft above floor level.
- 3D volume scan, maintaining a distance of 2 ft from all room surfaces, and 5 ft from the RSS, for 20 seconds. This measurement was repeated three times.

RSS at loudspeaker positions (b) and (c):

- 3D volume scan, maintaining a distance of 2 ft from all room surfaces, and 5 ft from the RSS, for 20 seconds. This measurement was repeated three times.

3.3 PARAMETER MEASUREMENT RESULTS

The test plan described in Section 3.2 was implemented in the four rooms to evaluate the test parameters that influence a measure of I-O noise reduction that can be related to that measured by the O-I method. There are several ways to measure the sound level generated by a loudspeaker in an enclosed space, but selection of the most appropriate depends on the type of sound field that is produced in a typical furnished room.

3.3.1 Direct vs Reverberant Sound Fields

In a large, unfurnished room, a loudspeaker will generate a reverberant sound field such that the sound level does not vary significantly throughout the room, and the average sound level can be measured by means of a 3D scan. However, in small rooms, and particularly those with furnishings, the direct sound field from a loudspeaker may dominate over the reverberant sound field for much of the room volume to a degree that depends on the amount of absorption in the room. The measurements performed in the first series of tests were designed to determine the extent of the direct sound field in small rooms and to test the feasibility of using the reverberant sound level to characterize the level to which the interior walls are exposed. The results of the measurement of the octave-band sound level as a function of distance from the loudspeaker are shown in Figures 8 and 9 for Test Houses 1 and 2, respectively.

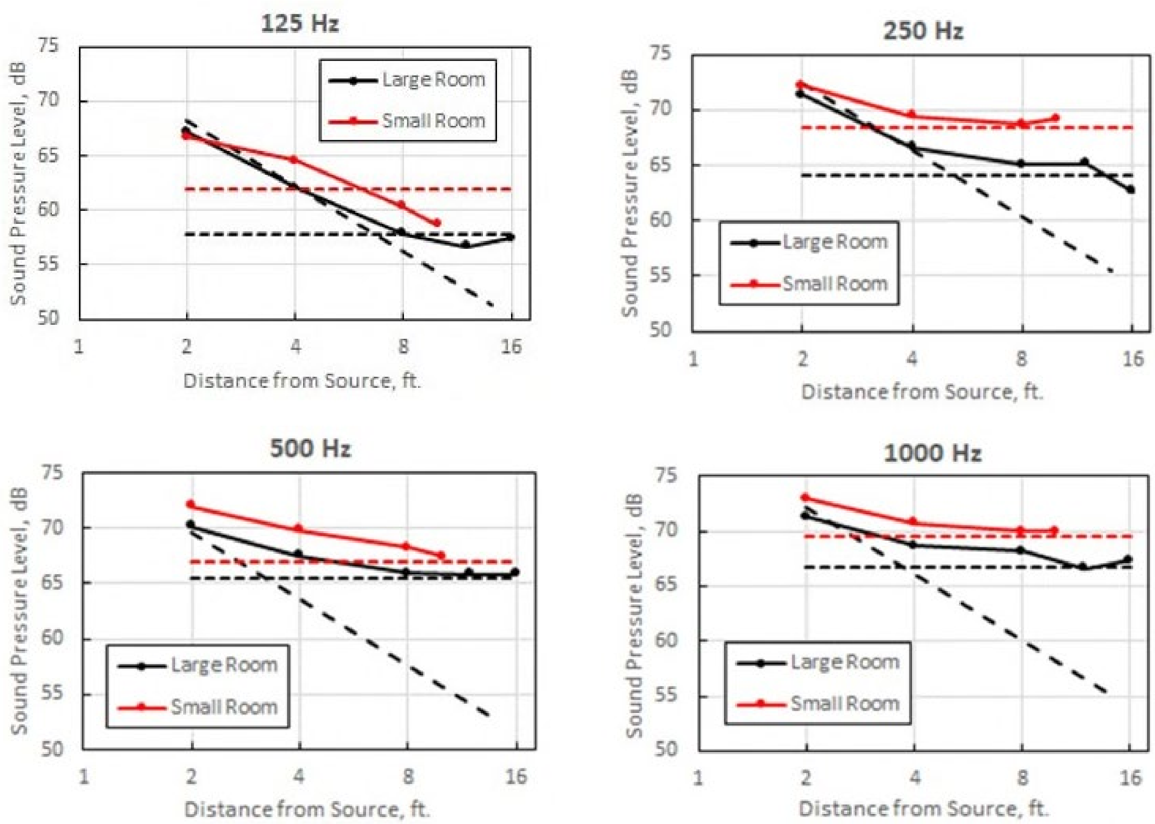


Figure 8. Sound Pressure Level as a Function of Distance for Large and Small Rooms of Test House 1

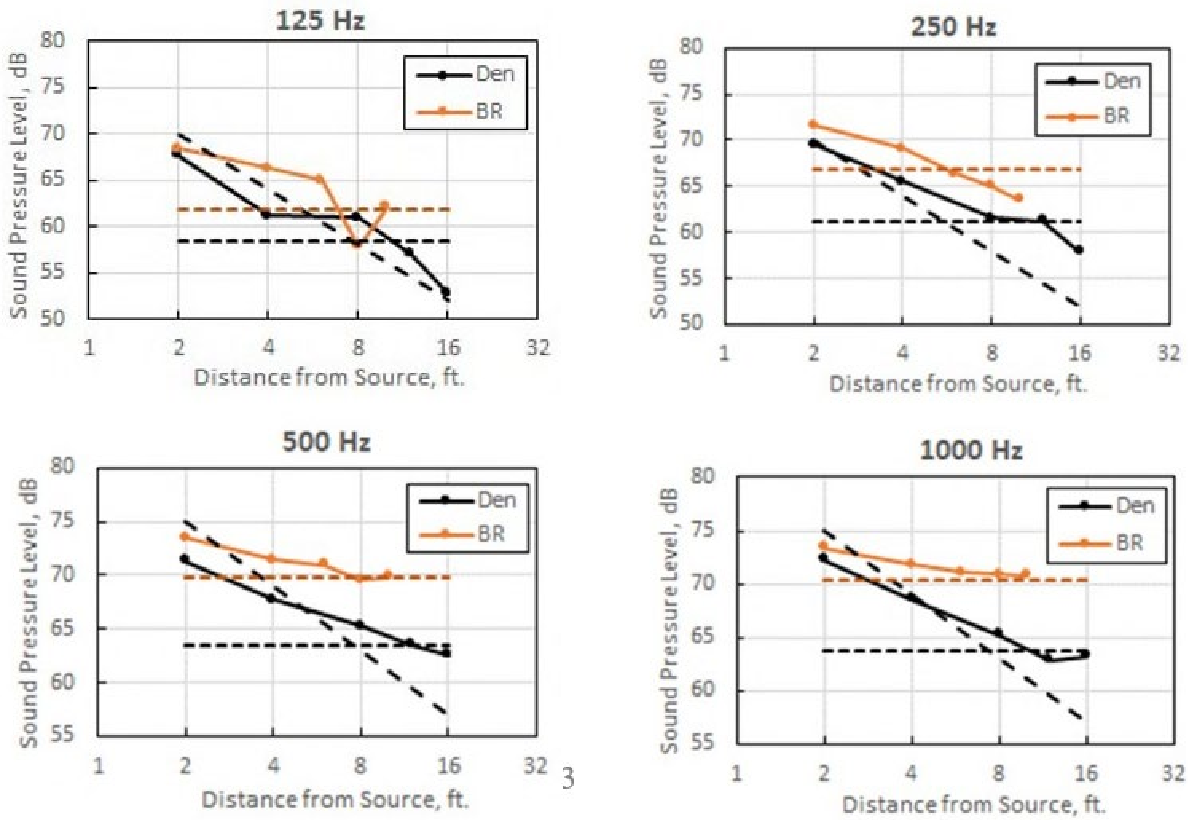


Figure 9. Sound Pressure Level as a Function of Distance for the Den and Bedroom of Test House 2

The data in these figures were obtained with an RSS placed in the corner of the rooms, corresponding to loudspeaker position (a) as described in Section 3.2. The data is presented in octave bands to reduce the influence of individual room modes.

The horizontal dashed lines in Figures 8 and 9 represent the reverberant sound level in the room, as measured by a 3D scan maintaining a distance of 2 ft from all room surfaces and at least 5 ft from the RSS. This reverberant level is determined by the amount of absorption in the room. The heavy, dashed lines show an inverse-square law relationship (6 dB per doubling of distance), that represents the decay of the direct sound field with distance from the source. The overall sound level at any point in the room is the sum of the direct and reverberant levels at that point.

The data presented in the figures generally follow the expected relationship with the direct sound field dominating at short distances, transitioning to an asymptotic value as distance increases. It is notable in Figures 8 and 9 that the direct sound field dominates the overall sound level out to distances varying from 5 to 8 ft from the source, depending on the frequency. As a result, a 3D scan to measure the reverberant sound level must be limited to the volume that is at least 5 ft from the source, and preferably more in rooms with higher absorption. In practice, this requirement, together with the need to maintain a distance of 2 ft from the walls, severely limits the volume over which the reverberant sound level can be measured in typical rooms. It is not difficult for the technician performing the measurement to accidentally move the microphone into the direct sound field from the loudspeaker and measure an interior sound level higher than the actual reverberant level. It is therefore not the most reliable technique for field measurement in small, furnished rooms.

3.3.2 Alternative Representations of the Interior Sound Field

The interior sound field to which a test wall is exposed can also be characterized by measuring the sound levels close to the surface of the wall by means of a 2D scan. As with the measurement of incident exterior sound level in the O-I test procedure, the sound field level incident to the interior surface is subject to interference from reflections (see Section 2.2.3), and so must be measured within 1 inch from the surface in order to avoid interference effects in the most important frequency range (see Figure 4). Complying with such a requirement may be difficult in practice as the wall surfaces in most furnished rooms are covered with pictures and other ornaments. An alternative method is to perform the measurement over the surface of the windows or doors which almost always provide access. When this measurement is conducted at a distance within 1 in. of the wall, a 3-dB correction factor must be applied to estimate the room reverberant level (see Equation (18)).

Measuring the sound level at a greater distance from the wall is complicated by the fact that the sound level in a reverberant sound field decreases rapidly with increasing distance from the wall (see Section 2.2.3). At 125 Hz, the distance at which the interference results in an increase in level of less than 0.5 dB from the room reverberant level is on the order of 24 in. (see Figure 5). Therefore, a 2D scan at a distance of 24 in. is an alternative method for measuring the reverberant sound level in a room without requiring the application of any correction factor. Maintaining a distance of 24 in. from *all* walls will result in a measurement distance of 34 in. from an edge, and 42 in. from a corner. According to the data in Figure 5, this may affect the errors in measurements below 200 Hz to 250 Hz.

From the results of the parameter tests, a comparison of the reverberant sound level, L_r, with the levels L_1 and L_{24} measured at distances of 1 in. and 24 in. from the wall surface respectively, for different loudspeaker orientations in the four rooms, is shown in Table 3.

Table 3. Relationships Between Sound Field Level Descriptors

Room	Loudspeaker Orientation	ΔdB*		
		$L_r - L_{24}$	$L_r - L_{1wall}$	$L_r - L_{1win}$
1A Large	Corner facing out	0.7	-2.1	-2.0
	Facing in at 3 ft	-0.1	-2.4	-2.0
	Facing out at 3 ft	-1.1	-3.3	-3.4
1B Small	Corner facing out	1.0	-2.3	-2.3
	Facing in at 3 ft	0.7	-1.6	-1.5
	Facing out at 3 ft	-0.3	-3.0	-3.6
2A N Wall	Corner facing out	0.2	-2.2	-2.2
	Facing in at 5 ft	0.2	-2.2	-3.0
	Facing out at 5 ft	0.6	-2.2	-2.2
2A W Wall	Corner facing out	1.5	-1.1	-1.9
	Facing in at 5 ft	0.4	-2.2	-2.1
	Facing out at 5 ft	0.7	-1.7	-2.7

Room	Loudspeaker Orientation	ΔdB*		
		$L_r - L_{24}$	$L_r - L_{1wall}$	$L_r - L_{1win}$
2B N Wall	Corner facing out	0.7	-2.1	-2.3
	Facing in at 5 ft	0.0	-2.3	-2.8
	Facing out at 5 ft	-0.4	-2.3	-3.1
2B E Wall	Corner facing out	0.7	-2.5	-2.9
	Facing in at 5 ft	0.4	-2.3	-2.6
	Facing out at 5 ft	0.2	-2.9	-3.1
Average		0.3	-2.3	-2.5
Standard Deviation		0.6	0.5	0.6

*L_r = Reverberant sound field level
L_{24} = 2D scan 24 in. from wall surface
L_{1wall} = 2d scan 1 in. over wall surface
L_{1win} = 2d scan 1 in. over window surface

As shown in Table 3, the level measured at 24 in., L_{24}, is a reasonably good representation of the reverberant sound level, L_r, and that the level L_{1wall}, measured 1 in. from the wall, is consistent with the theory that the level at the wall surface is 3 dB greater than the room reverberant level. Moreover, the scanned level at 1 in. from the window alone is an alternative measure where a 1-in. scan over the walls is not possible. The spectra for the scans over the wall and window and for the window alone are shown in Figure 10 to be within 0.5 dB at all frequencies greater than 125 Hz.

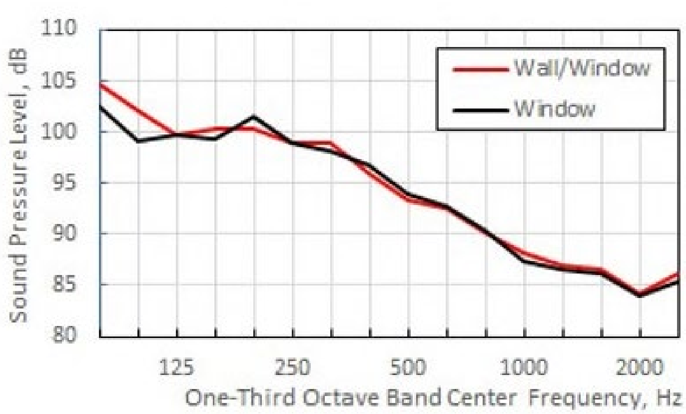


Figure 10. Spectral Characteristics of 2D Wall/Window and Window Scans

In practice, the windows are nearly always accessible once curtains have been opened and blinds raised.

Thus, the alternatives to performing a 3D scan to measure the reverberant level in the test room, in order of preference, are as follows:

1. 2D scan at 1 in. over the interior wall, or
2. 2D scan at 1 in. over the interior of the windows, or
3. 2D scan at 24 in. over the interior wall.

Practical considerations may dictate the final selection of measurement method.

3.3.3 Measurement of Room Absorption

In order for the I-O measurement method to simulate the results of the O-I measurement, the absorption of the test room must be considered (see Equation (25)). In the parameter tests, the room absorption was measured using a calibrated RSS, the Acculab RSS 101, consisting of a centrifugal fan operating at a fixed rotational speed to produce a specified sound power output. The procedure for measuring absorption requires a measurement of the average sound level in the room in the reverberant sound field produced by the RSS. The sound absorption, *A*, in the room is then given by the expression, derived from Equation (13) in Section 2.2.2:

$$A = 43.1\ x\ 10^{\frac{PWL-SPL}{10}}\ \text{sq ft}$$

where PWL is the sound power level of the RSS re 1 pW, and *SPL* is the sound pressure level in the room produced by the RSS re 2 x 10^{-5} N/m^2. The absorption is calculated in square feet in one-third octave frequency bands. The sound power output, *PWL*, of the reference source is a constant value for the source measured according to ISO Standard (ISO, 2016b) in a reverberation chamber with the source placed on the floor away from all wall surfaces so that the output is not influenced by the interference effects described in Section 2.2.4. The absorption is therefore dependent only on the reverberant sound level.

The placement of the RSS is important when it is used to measure absorption in a furnished room. If it is placed close to a corner, the output can increase by up to 9 dB. As the source is moved away from the corner, its output drops and becomes a minimum when the distance to the wall or corner is about one-half a wavelength. At larger distances, the output will cease to be affected by the room surfaces, and will approach that as measured in the ISO standard.

The sound pressure level, *SPL*, in the room will vary with the changes in sound power output with position, and hence so also will the calculated absorption. This effect is clearly evident in the data presented in Figure 11 for absorption measurements in the two rooms of House #1. The solid lines in this figure represent the measured absorption with the RSS in the corners of the large and small rooms; the dashed lines represent the absorption as measured with the RSS 3 ft away from the corners. The latter clearly show a minimum in the measured absorption in the frequency range 250 Hz to 400 Hz, corresponding to a one-half wavelength for a distance of about 2 ft, which was the closest edge of the finite-sized source from the corner.

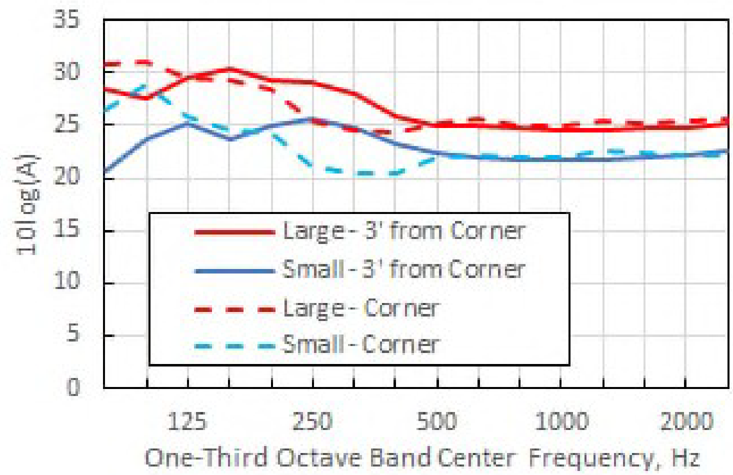


Figure 11. Measured Absorption as a Function of Frequency

The measurement of room absorption should therefore be conducted with the reference sound source placed at least 5 ft from the corner to ensure that the source output is consistent with that as measured by the ISO standard procedure.

3.3.4 Noise Reduction Measurement Parameters

The data gathered from the measurements conducted in the four rooms as part of the parameter tests were used to calculate the noise reduction of each individual wall in each room for a range of parameters, including source position, interior level descriptor (L_r, L_{24}, and L_1 window only), and exterior level measurement distance.

The I-O noise reduction, NR_{IO}, was calculated in one-third octave bands according to the relationship in Equation (25). The spectral noise reduction values were then subtracted from typical aircraft arrival and departure spectra (Sharp et al., 2018) to determine the corresponding one-third octave band and A-weighted interior levels for aircraft arrivals and departures. The I-O noise level reduction (NLR_{IO}) was calculated as the difference between the resulting A-weighted exterior and interior sound levels. The value of NLR_{IO} for the I-O measurements was then compared with the corresponding NLR_{OI} obtained from the O-I measurements conducted according to the ARP 6973 standard.

The difference in calculated values of O-I and I-O NLR are presented in Table 4for the different parameters. In this table, the differences in NLR values are shown for exterior level measurements at a range of distances (6, 12, 24, and 36 in.) from the facade surface.

Table 4. Calculated I-O – O-I NLR for a Range of Measurement Parameters with K = 12

Room	Loudspeaker	K	I-O – O-I NLR for Interior Measurement of:							
			L_r				L_{24}		L_1	
			6 in.	12 in.	24 in.	36 in.	24 in.	36 in.	24 in.	36 in.
1. Large	Corner facing out	12	-7.0	-7.1	-5.8	—	-6.3	—	-6.1	—
	3 ft from corner, facing in		-6.9	-6.3	-3.6	—	-3.7	—	-3.9	—
	3 ft from corner, facing out		-7.2	-6.2	5.8	—	-5.2	—	-4.4	—
1. Small	Corner facing out	12	-8.3	-6.4	-5.7	—	-7.3	—	-5.6	—
	3 ft from corner, facing in		-5.3	-2.2	-1.2	—	-2.5	—	-2.0	—
	3 ft from corner, facing out		-7.4	-4.7	-3.5	—	-3.6	—	-3.8	—
2. Den N Wall	Corner facing out	12	—	—	-1.7	-0.1	-2.3	-0.8	-2.1	-0.4
	5 ft from corner, facing in		—	—	-1.6	0.1	-2.3	-0.6	-2.1	-0.5
	5 ft from corner, facing out		—	—	-1.4	-0.4	-1.6	0.1	-1.9	-0.9
2. Den W Wall	Corner facing out	12	—	—	1.9	2.7	-0.7	0.1	1.3	2.0
	5 ft from corner, facing in		—	—	1.0	2.0	-0.8	0.2	0.8	1.7
	5 ft from corner, facing out		—	—	0.8	2.0	-0.7	0.6	0.4	1.6
2 BR N Wall	Corner facing out	12	—	—	-5.6	-3.4	-6.1	-4.0	-5.8	-3.6
	5 ft from corner, facing in		—	—	-2.7	-1.5	-2.1	-1.0	-2.6	-1.2
	5 ft from corner, facing out		—	—	-4.2	-3.1	-4.4	-3.1	-4.1	-2.9
2 BR E Wall	Corner facing out	12	—	—	-2.8	-1.5	-5.4	-4.2	-2.5	-1.2
	5 ft from corner, facing in		—	—	-1.2	0.0	-1.8	-0.4	0.1	1.4
	5 ft from corner, facing out		—	—	-1.6	0.4	-2.8	-0.8	-1.8	0.2

The I-O values used in the determination of the differences in Table 4 are calculated according to Equation (25), and are thus dependent on the value of the constant K. In the case of a completely diffuse interior sound field, and for $TL = TL_\Theta$, the value of K is 12. For comparison purposes, this value is assumed in the calculations for Table 4. If the sound field is not diffuse, then a value of K less than 12 may be more appropriate to adjust the I-O value of NLR to match the O-I value.

3.3.4.1 Noise Source Position

Reviewing the data for each room individually in Table 4, the deviation from zero for all measurement metrics is generally less pronounced with the loudspeaker 5 ft from, and facing in towards, the corner, than for other positions, indicating that this position may be generating a more diffuse sound field. This result is consistent with ASTM recommended practice (ASTM, 2019) in that in this position, the loudspeaker exposes the test walls to a more diffuse sound field rather than to direct sound.

It should be noted that it is not always possible to position a bulky loudspeaker 5 ft from a room corner. In some situations, notably for the large room in the first series of parameter tests, there were no specific room corners available, and the loudspeaker had to be placed close to a corner between a cabinet and the wall. The most important factor is that the main axis of the loudspeaker should not be pointed towards the test facade, but should be directed towards the nearby corner, thus increasing the sound field diffusion.

The results for the large and small rooms in the first parameter tests also followed the same trend, but in absolute values, the deviations were larger than for the rooms in the second parameter tests, indicating that a value for K less than 12 would be appropriate.

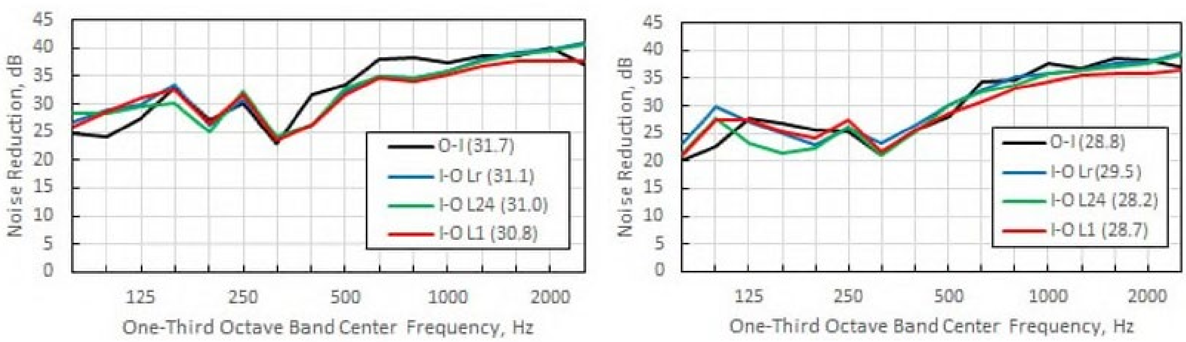
3.3.4.2 Exterior Sound Level Measurement

The exterior levels generated by sound transmission through, and radiation from, the wall generally decrease with increasing distance, resulting in an increase in measured I-O noise reduction. However, as described in Section 2.3, at positions very close to the surface of the wall, the relationship between sound pressure and distance is complex. At small distances, the sound level oscillates about a mean value. As the distance increases, the radiation is in the form of a plane wave, until a distance beyond which the propagation assumes the characteristics of a line source, and as the distance increases, eventually a point source. The difference between the I-O and O-I measurements of noise reduction will therefore decrease with distance accordingly. In the parameter tests, the exterior levels were measured at various distances to verify the conclusions of Section 2.3, as expressed in Table 2, and to identify a distance over which the propagation could be considered as a plane wave.

The differences in I-O and O-I NLR presented in Table 4 as a function of exterior measurement distance shows a gradual decrease in the deviation, and hence an increase in measured I-O noise reduction, with increasing distance. The behavior over distances from 6 to 12 in. is somewhat consistent with Freedman's (1960) conclusions that the sound pressure oscillates about a mean value. At distances from 24 to 36 in., the sound pressure level decreases, and the measured I-O noise reduction increases, at the rate of 3 dB per doubling of distance, which is characteristic of propagation from a line source. As a result, it would appear that the transition of the propagation from a near-field oscillation to that from a line source, for an A-weighted measure such as NLR, occurs in the region from 12 to 24 in. from the radiating surface, consistent with the conclusions of Table 2.

3.3.4.3 Interior Sound Level Metrics

The parameter tests included measurements of noise reduction using three different metrics, namely L_r, L_{24}, and L_1, for describing the interior sound levels to which the test wall was exposed. Figure 12 shows a comparison of the measured values of noise reduction for the large and small rooms, in which the loudspeaker was placed 3 ft from, and facing, the corner, in the first series of parameter tests, where values of K have been selected for the best matching of the I-O and O-I noise reduction spectra. Exterior sound levels were all measured by means of a 2D scan at a distance of 24 in.



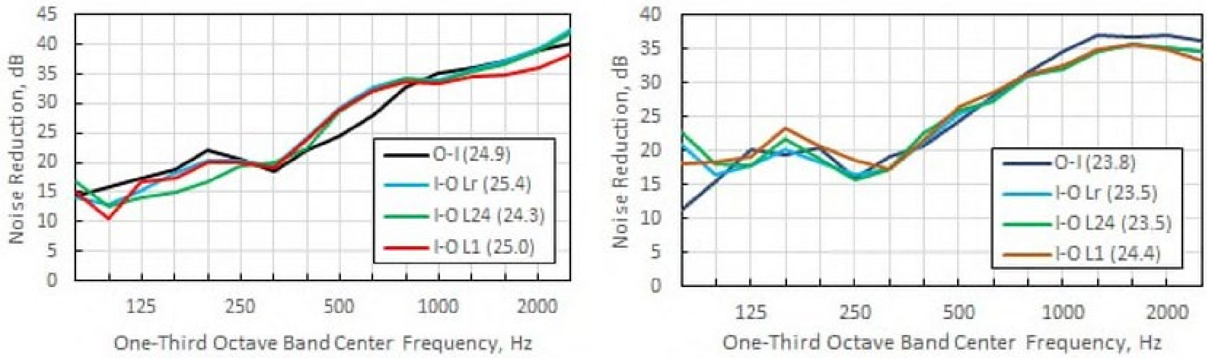
(a) Large Room with K = 9 (b) Small Room with K = 10

Figure 12. Comparison of O-I and I-O Noise Reduction for Parameter Tests 1

The data for the large room shows a close agreement in spectra and NLR values between noise reduction calculated for the different measurement metrics and with K = 9. The agreement with the O-I data, however, is good only at frequencies below 315 Hz, closely following the peaks and dips in the curve. At higher frequencies, the I-O data is consistently lower by 2 dB to 5 dB, even though the NLR values are within 1 dB of the O-I data. It is possible that these lower values are the result of background noise occurring during the exterior measurements.

The data for the small room also shows a close agreement between I-O and O-I measurements both in spectra and NLR value for all metrics, but this time with K = 10. However, it is noticeable that the L_{24} measurement (at 24 in. from the test wall) provides lower values in the frequency range 125 Hz to 200 Hz, the result of reflection interference from the test wall at a distance of 24 in., consistent with the conclusions of Section 2.5.

Similar comparisons of I-O and O-I measured data for the second series of parametric tests, with the loudspeaker placed 5 ft from, and facing, the room corner, are presented in Figure 13.



(a) Den with K = 11 (b) Bedroom with K = 10

Figure 13. Comparison of O-I and I-O Noise Reduction for Parameter Tests 2

The data for the den in Figure 13(a), with K = 11, shows agreement between the I-O and O-I measurements for L_r and L_1 at frequencies less than 315 Hz, but there is some deviation in the range 400 Hz to 800 Hz due to airborne flanking transmission via an adjoining room that reduces the O-I noise reduction measured with an outdoor loudspeaker. The I-O measurement procedure does not allow for the inclusion of airborne flanking transmission from adjoining spaces. The relatively close numerical agreement between the O-I and I-O measurements of NLR, despite significant differences in frequency spectra, is one of the consequences of using a single-number noise reduction metric.

The I-O noise reduction, L_{24}, measured by means of an indoor 2D scan at 24 in. also shows the same deviation at low frequencies as in the small room in Figure 12. Otherwise, despite the deviation of the other metrics at higher frequencies, the I-O NLR values for L_r and L_1 are within 0.5 dB of the O-I measurements.

Figure 13(b) presents the data for the bedroom that is adjacent to the den. In this case, the agreement between the I-O and O-I measurements is within 0.6 dB for all metrics despite minor deviations in the 125 to 250 Hz frequency range. Table 5 presents a summary of NLR values for the four test rooms calculated using each of the three metrics for measurement of the interior sound level.

Table 5. Summary of O-I and I-O NRL for Parameter Test Rooms

Room	K	O-I NLR, dB	I-O NLR, dB		
			L_r	L_{24}	L_1
Large	9	31.7	31.1	31.0	31.8
Small	10	28.8	29.5	28.2	28.7
Den	11	24.9	25.4	24.3	25.0
BR	10	23.8	23.5	23.5	24.4

The variation in values of the NLR across the three metrics for any given room is 0.7 dB or less, albeit with different optimum values of K for each room. Of the three metrics, the values for L_1 (window only) are generally closest to the O-I values.

3.4 CONCLUSIONS FROM THE PARAMETER TESTS

The parameter tests were designed to evaluate the elements of an I-O test procedure for the measurement of noise reduction. The conclusions from the results of the tests are:

- Sound levels in furnished rooms are far from diffuse. In a typical furnished room, the direct sound field extends at least 5 ft from the noise source, more or less as room absorption is increased or decreased. As a result, there is a limited volume in the room in which to measure the reverberant sound level.

- The optimum position for the noise source to generate a uniform reverberant sound field in the room is at least 3 ft, and preferably 5 ft, from a corner of the room, facing towards the corner to increase the diffuseness of the sound field.

- Room absorption should be measured with the reference sound source placed at least 5 ft from the corner of the room.

- Although the data is limited, measuring the I-O NLR of a facade using the L_1 metric appears to show the best comparison with the O-I measurement. The L_{24} measurement can be used as an alternative.

- The measurement of L_1 over the entire wall surface can be replaced by measurement over just the window surfaces.

- The exterior sound level should be measured at a distance of 24 in. from the facade.

- The I-O method for measuring noise reduction, which measures only the transmission of sound through the test facade, is generally not applicable, nor is it a preferred procedure, in the presence of airborne flanking transmission from adjoining rooms.

4. FIELD VALIDATION TESTS

4.1 OBJECTIVES

Incorporating the results from the parameter tests, field measurements were performed to develop best practices for conducting the I-O noise reduction measurements, and to demonstrate equivalence with the O-I method. An important part of these measurements was to determine whether a single value of K could be established for a range of different room types.

Measurements were conducted in four rooms in each of two houses located adjacent to Louisville International Airport to validate the concept of an I-O measurement methodology by comparing the results with simultaneous measurements obtained using the standard O-I procedure.

4.2 VALIDATION TEST PLAN

4.2.1 Test Room Conditions

- Curtains opened, and window blinds raised.
- All doors closed; prime and storm windows closed and locked.
- Furniture left in place where possible, except when required to position loudspeaker and conduct area scans.

4.2.2 O-I Loudspeaker Measurements

- Loudspeaker: Mackie SRM350
- Noise Spectrum: Pink noise

ARP 6973 guidelines were followed for exterior loudspeaker distance, height, and angle of incidence. Where possible, measurements were conducted on corner rooms with a loudspeaker positioned diagonally to the corner, with separate 2D scans over each wall.

4.2.3 I-O Loudspeaker Measurements

- Loudspeaker: Mackie SRM350
- Noise Spectrum: Pink noise
- Loudspeaker output monitor microphone at 1 ft on axis
- Two loudspeaker positions for rooms with one and two exterior facades (see Figure 14(a) and (b)):

    a) Along room diagonal, facing far corner from exterior walls, at a distance of 3 ft from the corner
    b) Along room diagonal, facing far corner from exterior walls, at a distance of 5 ft from the corner

- Two loudspeaker positions for rooms with three exterior facades (see Figure 14(c)):

    c) In central part of room, away from the three exterior facades, angled at 45 degrees to the interior wall, and 3–4 ft from the wall

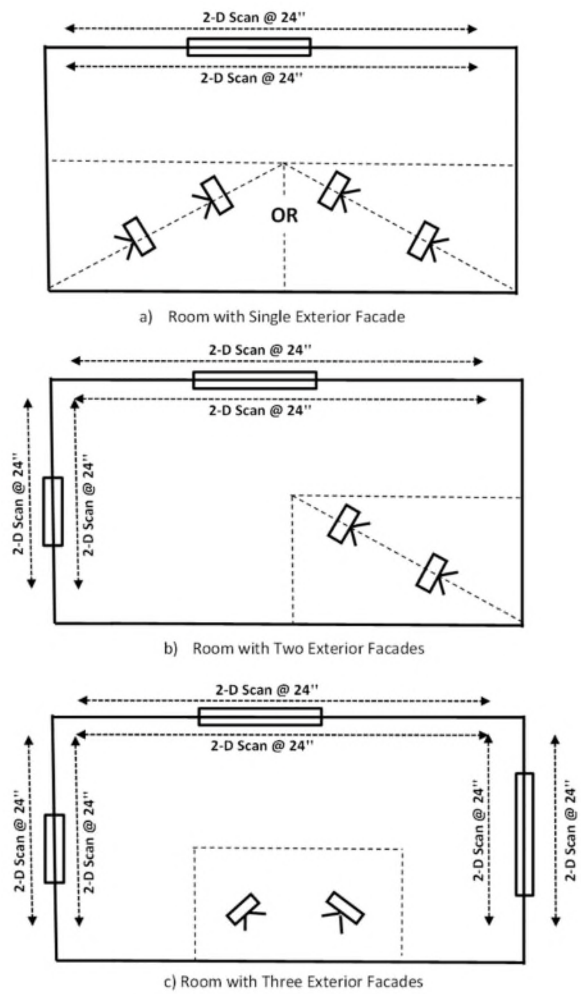


Figure 14. Example Loudspeaker Positions for I-O Measurement

Interior sound level measurements for all loudspeaker S positions:

- 2D scans over each interior wall/window area (separate scans for each wall) at a distance of 24 in. for 20 seconds each. The scans were performed over the central area of each wall (including the windows and doors), not including areas within 2 ft of the floor, ceiling, or edges of the room. Small items of furniture were moved as necessary to conduct the scans. Scans were not performed over walls shielded by bookcases or large items of furniture, in which case the sound level measured over the window only was used as the interior level.

- 2D scan over each window at a distance of 1 in. for 15 seconds.

Exterior sound level measurements for both loudspeaker positions maintaining the same power output level as for the interior measurements as measured by the monitoring microphone:

- 2D scan over each wall/window area (separate scans for each wall) at a distance of 24 in. from the exterior surface for 20 seconds, not including areas within 2 ft of the horizontal and vertical edges of the room. The scanned area corresponded to the same area as for the interior scans.

- Exterior measurement of background noise level in the absence of loudspeaker output at a single position 24 in. from the center of each exterior wall for at least 15 seconds.

4.2.4 Reference Sound Source Measurements

- Reference Sound Source (Acculab RSS 101):
  - RSS at floor level at each of the two loudspeaker positions, with sufficient space to measure reverberant sound level in the room.
  - 3D sound level scans, maintaining a distance of 2 ft from all room surfaces, and 5 ft from the RSS, for 20 seconds.

4.3 VALIDATION TEST HOUSES

The validation tests were conducted in two houses, identified as House #3 and House #4, the floorplans of which are shown in Figures 15 and 16. In each floorplan, the large arrows indicate the exterior loudspeaker positions (distances not to scale) used for the O-I tests in each room.

Both houses were one-story buildings with insulated attic space. House #3 was constructed with vinyl siding on all exterior facades, with a partially enclosed porch area at the front. Three of the rooms had two exterior facades, each with a window. The dining room had one exterior facade with a large window area. As a result of limited access to the area adjacent to the dining room, the loudspeaker for the O-I measurements could only be positioned 9 ft from, and at 0 degrees to, the facade.

House #4 was a wood-frame construction with brick veneer exterior, having an add-on dining room of vinyl siding at the rear. The dining room had a bay window and was connected to the kitchen, forming a combined kitchen/dining area with three exterior facades. The other three test rooms had two exterior facades each with a window, except the living room that had one windowless facade.

Figure 15. Floorplan of House #3

Figure 16. Floorplan of House #4

To avoid complications with the porch in these validation tests, the NLR measurement for Bedroom 1 in House #4 did not include a measurement of the porch facade and is therefore representative of the other facade only.

4.4 VALIDATION TEST RESULTS

The test plan described in Section 4.2 was implemented in four rooms each in Houses #3 and #4, and the values of the noise level reduction measured by the I-O and O-I procedures compared to validate the I-O test procedure.

The general form of the expression for the I-O noise reduction derived in Equation (25) of Section 2.4.2 is:

$$NR_{IO} = L_r - L_t - 10\log(S/A) - K$$

where L_r is the interior reverberant level in the room, L_t is the level measured close to the exterior of the facade, and K is a constant, approximately equal to 12 if the interior sound field is diffused but may assume lesser values in sound fields with lower diffusion. In accordance with the conclusions of Section 3.4, the measurement of interior reverberant level L_r was replaced by measurements close to the interior facade, namely:

- L_1—a 2D scan at 1 in. from the interior window surfaces. A constant 3 dB was subtracted from the measured value to account for the effect of wall reflection in a reverberant sound field.

- L_{24}—a 2D scan at 24 in. from the wall surface.

The results obtained from the field measurements are presented in Table 6 for each of the eight rooms tested in Houses #3 and #4. In addition, the data for Houses #1 and #2 from the first and second parameter tests are included. The measured values of NLR_{OI} are shown in the third column of the table. The remaining columns show the values of NLR_{IO} for the two measurements of interior level, L_{24} and L_1, each for loudspeaker S positions 3 and 5 ft from the room corner, facing in towards the corner. Exterior sound levels were measured by means of a 2D scan 24 in. from the facade. The data is presented for calculated values of NLR_{IO} for values of K from 10 to 12.

Table 6. NLR Data from the Field Validation Tests

House	Room	O-I NLR	I-O NLR (L_{24})						I-O NLR (L_1)					
			LS at 3 ft			LS at 5 ft			LS at 3 ft			LS at 5 ft		
			K=10	K=11	K=12	K=10	K=11	K=12	K=10	K=11	K=12	K=10	K=11	K=12
1	LR	31.7	30.0	29.0	28.0	—	—	—	29.8	28.8	27.8	—	—	—
	BR	28.8	28.2	27.2	26.2	—	—	—	28.7	27.7	26.7	—	—	—
2	Den	24.9	—	—	—	25.3	24.3	23.3	—	—	—	26.1	25.1	24.1
	BR	23.8	—	—	—	23.7	22.7	21.7	—	—	—	24.4	23.4	22.4
3	LR	26.9	28.1	27.1	26.1	28.0	27.0	26.0	28.3	27.3	26.3	28.1	27.1	26.1
	BR1	25.3	25.4	24.4	23.4	25.0	24.0	23.0	26.1	25.1	24.1	26.2	25.2	24.2
	BR2	23.0	26.0	25.0	24.0	24.5	23.5	22.5	27.9	26.9	25.9	25.5	24.3	23.3
	DR/K	22.2	23.3	22.3	21.3	23.5	22.5	21.5	24.1	23.1	22.1	25.3	23.2	22.2
4	LR	22.9	24.2	23.2	22.2	23.5	22.5	21.5	24.1	23.1	22.1	24.1	23.1	22.1
	BR1	26.0	27.6	26.6	25.6	27.8	26.8	25.8	27.9	26.9	25.9	28.5	27.5	26.5
	BR2	24.8	24.6	23.6	22.6	26.8	25.8	24.8	24.9	23.9	22.9	26.9	25.9	24.9
	DR	22.3	25.8	24.8	23.8	24.0	23.0	22.0	26.1	25.1	24.1	24.5	23.5	22.5

In order to identify the measurement and calculation method that provides the best agreement between NLR_{OI} and NLR_{IO}, the data in Table 6 is reformatted and presented in Table 7 to compare the differences in values of the two quantities for the different loudspeaker positions, the interior noise metrics, and the value of the constant K.

Table 7. O-I and I-O NLR Data Comparison from the Field Validation Tests

House	Room	ΔNLR = O-I – I-O NLR(L_{24})						ΔNLR = O-I – I-O NLR(L_1)						ΔNLR(L_1)
		LS at 3 ft			LS at 5 ft			LS at 3 ft			LS at 5 ft			LS at 5 ft
		K = 10	K = 11	K = 12	K = 10	K = 11	K = 12	K = 10	K = 11	K = 12	K = 10	K = 11	K = 12	K = 11.5
1	LR	1.7	2.7	3.7	—	—	—	1.9	2.9	3.9	—	—	—	—
	BR	0.6	1.6	2.6	—	—	—	0.1	1.1	2.1	—	—	—	—
2	Den	—	—	—	-0.4	0.6	1.6	—	—	—	-1.2	-0.2	0.8	0.3
	BR	—	—	—	0.1	1.1	2.1	—	—	—	-0.6	0.4	1.4	0.9
3	LR	-1.2	-0.2	0.8	-1.1	-0.1	0.9	-1.4	-0.4	0.6	-1.2	-0.2	0.8	0.3
	BR1	-0.1	0.9	1.9	0.3	1.3	2.3	-0.8	0.2	1.2	-0.9	0.1	1.1	0.6
	BR2	-3.0	-2.0	-1.0	-1.5	-0.5	0.5	-4.9	-3.9	-2.9	-2.5	-1.3	-0.3	-0.8
	DR/K	-1.1	-0.1	0.9	-1.3	-0.3	0.7	-1.9	-0.9	0.1	-3.1	-1.0	0.0	-0.5
4	LR	-1.3	-0.3	0.7	-0.6	0.4	1.4	-1.2	-0.2	0.8	-1.2	-0.2	0.8	0.3
	BR1	-1.6	-0.6	0.4	-1.8	-0.8	0.2	-1.9	-0.9	0.1	-2.5	-1.5	-0.5	-1.0
	BR2	0.2	1.2	2.2	-2.0	-1.0	0.0	-0.1	0.9	1.9	-2.1	-1.1	-0.1	-0.6
	DR	-3.5	-2.5	-1.5	-1.7	-0.7	0.3	-3.8	-2.8	-1.8	-2.2	-1.2	-0.2	-0.7
Average*		-1.5	-0.5	0.5	-1.0	0.0	1.0	-2.0	-1.0	0.0	-1.8	-0.6	0.4	-0.1
Maximum Range*		3.7	3.7	3.7	2.3	2.3	2.3	4.8	4.8	4.8	2.5	1.9	1.9	1.9

*Calculated for Houses 2 through 4

Examining the data in Table 7 shows that the measurements with the loudspeaker 3 ft from the room corner tend to exhibit a greater range of values for measurements of NLR for both L_1 and L_{24} than for those with the loudspeaker at 5 ft from the corner. This result is consistent with the conclusions of Section 3.4, which suggests that the minimum distance from a corner should be at least 5 ft. At loudspeaker distances less than this, the spectrum of the sound field in the room can be distorted in the low-frequency region.

The data in Table 7 also shows that measurements using L_{24} to represent the interior sound level have a greater range than those using L_1. At a distance of 24 in. from the wall, the sound field at the lowest frequencies is influenced by interference effects from wall reflection, with the result that the measured sound level may not correspond to the reverberant level in the room. The measurement using L_1 to represent the interior sound level shows the least variation across the 10 rooms, and hence is the recommended metric for measurement of the I-O noise reduction, NLR_{IO}. The L_{24} metric can be considered as an alternative measure for situations where measurements at 1 in. are not possible. Measurements should not be performed at intermediate distances.

Consequently, the procedure that shows the smallest range of values and the lowest average value is that using L_1 for the interior level with a loudspeaker at 5 ft from the corner. For this combination, the optimum value for K lies between 11 and 12. Using a value for K of 11.5, a comparison of the accuracy of the I-O test method, relative to the standard O-I method, is shown in Table 7 and Figure 17.

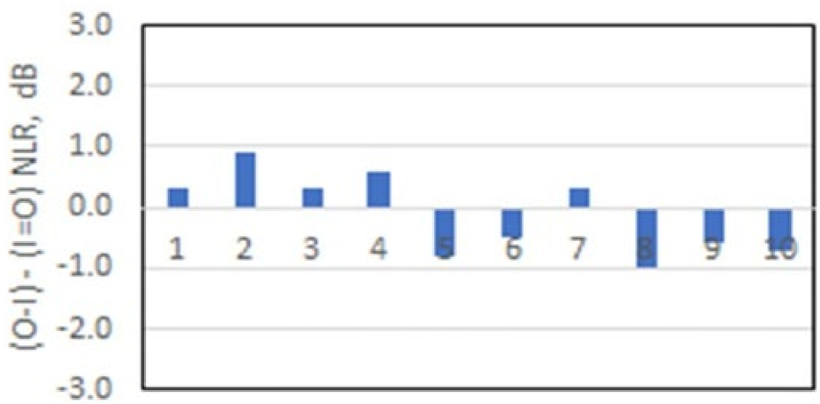


Figure 17. Comparison of the O-I and L_1 I-O Test Methods for K = 11.5

The differences between the O-I and I-O measurements for the 10 rooms tested are all within ±1 dB, the average difference being -0.1 dB.

The lowest average value of the differences between the two methods of NLR measurement using the L_{24} metric to define the interior level is obtained with a value of K = 11. A comparison of the accuracy of the I-O test method using the L_{24}metric is shown in Figure 18.

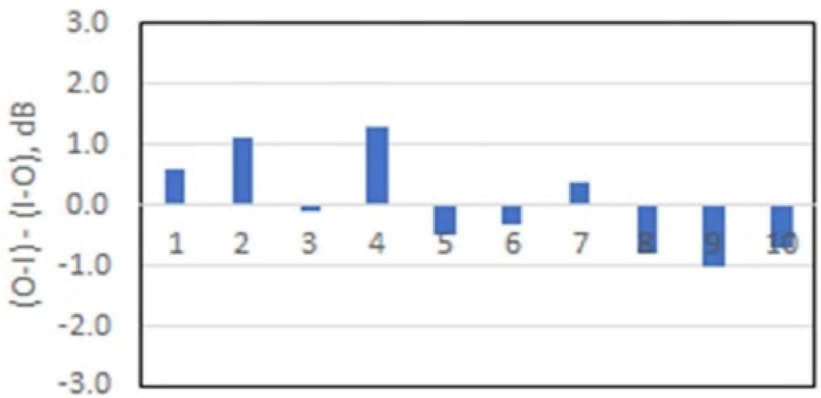


Figure 18. Comparison of the O-I and L_{24} I-O Test Methods for K = 11

The differences between the O-I and I-O measurements for the 10 rooms tested are all within +1.3/-1.0 dB, marginally larger than for the L_1 metric, and the average difference is 0 dB. The frequency spectra for the noise reduction measurement by the two methods are shown in Figures 19 and 20 for the 10 rooms tested, with the L_1 method of measurement and the value of K = 11.5.

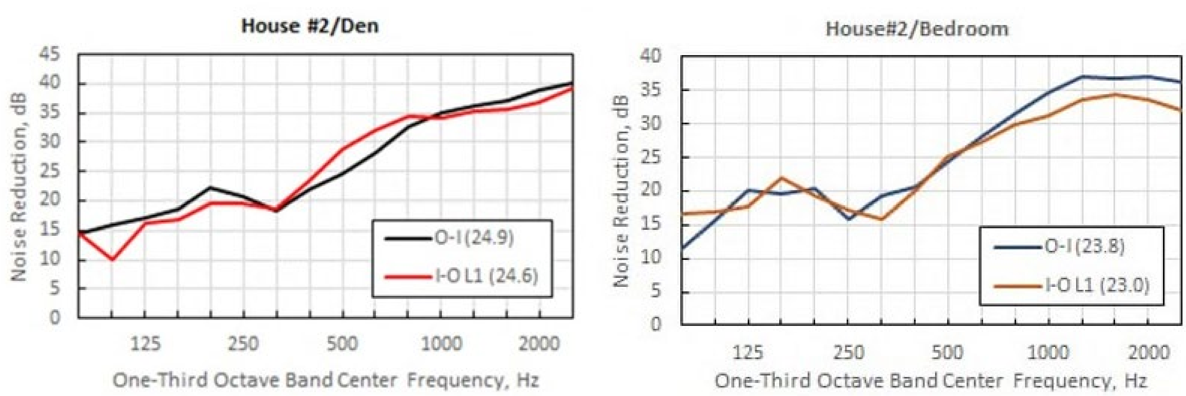


Figure 19. Noise Reduction Frequency Spectrum for House #2 with K = 11.5

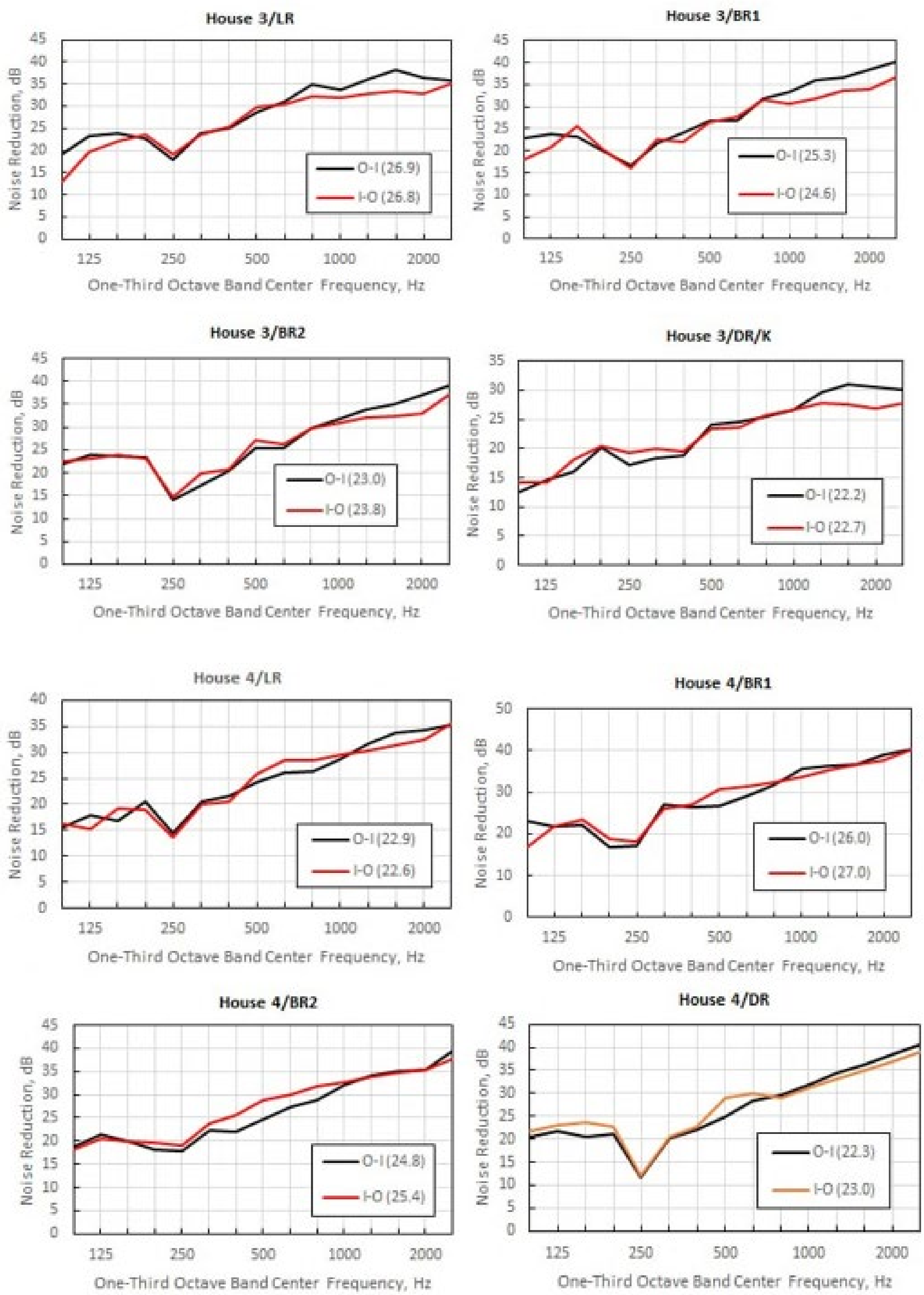


Figure 20. Noise Reduction Frequency Spectrum for Houses #3 and #4 with K = 11.5

In general, the agreement is close, with minor exceptions occurring at frequencies greater than 1,000 Hz. In this frequency region, background noise levels were sometimes within 6 dB of the exterior levels, making corrections difficult to apply. However, whereas noise reduction measurements are performed over the frequency range 100 Hz to 4,000 Hz, deviations at high frequencies have little to no influence on the value of the single-number NLR metric, the value of which is largely determined by the noise reduction at frequencies in the range 125 Hz to 500 Hz. At these frequencies, the background noise levels were 15 dB to 20 dB less than the exterior levels generated by the loudspeaker.

5. ALTERNATIVE METHOD FOR MEASURING I-O NLR

The results presented in Section 4 demonstrate the feasibility of using an indoor-outdoor I-O method for measuring NLR with good accuracy compared to the O-I method, while recognizing the limited sample of rooms and houses tested. The I-O method therefore potentially represents an alternative procedure to the standard O-I method where exterior loudspeaker placement may prove difficult. However, while it is a relatively simple procedure, it does require a measurement of room absorption, as well as requiring additional equipment in the form of a reference sound source. The absorption measurements are required in order to provide NLR data consistent with that measured using the O-I method.

An alternative method for measuring I-O noise reduction is to redefine the definition of noise reduction as the difference in sound power generated by the loudspeaker, W_S, and the sound power, W_t, transmitted to the exterior via the test facade, namely:

$$NR_{IOAlt} = 10\log\left(\frac{W_S}{W_t}\right)$$

Since the sound power transmitted includes the effect of absorption, but the loudspeaker sound power does not, the difference between the two quantities includes the influence of absorption, and hence is consistent with the standard O-I measurement. The numerical values of the two quantities would not necessarily be the same because they represent different definitions of noise reduction, but as they both measure the attenuation of noise by the test wall, they should be related to one another. The advantage of this alternative method is that it does not require a measurement of absorption. This section of the report describes the details of the alternative I-O method and relates the measured value of the new definition of noise reduction to the standard O-I measured value.

5.1 CALCULATION OF LOUDSPEAKER SOUND POWER OUTPUT

The sound power output of a loudspeaker in a room depends on the power generated and its location with respect to the room surfaces. When situated far from these surfaces, an omnidirectional source radiates sound equally in all directions and the sound power output is essentially the same as if it were outdoors in free space, as in Equation (14), namely:

$$W_S = 4\pi x^2\left(\frac{p_x^2}{\rho c}\right) \quad (26)$$

where p_x is the root-mean-square sound pressure at a distance x from the source, and ρc is the characteristic impedance of air, equal to 407 meter, kilograms, and seconds (mks) units at normal temperature and pressure.

The noise source used in the field validation tests described in Section 4 was a Mackie Model 350 loudspeaker with a 10-in. low-frequency cone diaphragm, together with a ¼-in. high-frequency dome driver. When placed on the floor, the center of the 10-in. low-frequency driver diaphragm is 10.25 in. above the floor. According to the data in Figure 4 of Section 2.2.3, assuming the low-frequency driver is a point source at this distance from the floor, its sound power output is unaffected by the presence of the floor at frequencies greater than 315 Hz. The loudspeaker effectively radiates into free space, as described in Equation (14). As the frequency is decreased below 315 Hz, the output is affected—increased more by the nearby surface (as shown in Figure 4); until at approximately 125 Hz, the loudspeaker is essentially radiating into a hemispherical space, as described by the expression:

$$W_S = 2\pi x^2 \left(\frac{p_x^2}{\rho c}\right) \tag{27}$$

At frequencies between 315 Hz and 125 Hz, the output can be calculated by interpolating between Equations (26) and (27) using the information in Figure 4.

The sound power output of the loudspeaker can therefore be calculated by measuring the sound pressure level at a distance x along the axis of the low frequency driver. This level should be measured sufficiently close to the loudspeaker so as to be in the direct sound field. For the field validation tests, the level was measured at a distance of 1 ft (0.33 m) on the loudspeaker axis.

However, Equations (26) and (27) are appropriate only if the source, in this case a loudspeaker, is a point source and is omnidirectional. Loudspeakers tend to be omnidirectional only at low frequencies, becoming more directional with increasing frequency. Equations (26) and (27) need to include a directivity factor, Q, to account for this behavior, where Q is defined as the ratio of the intensity on the main axis of the loudspeaker to the intensity that would be produced by an omnidirectional, point source, radiating the same total power as the loudspeaker. The value of Q is always equal to or greater than 1; actual values for loudspeakers are often provided by the manufacturer in the form of the directivity index, DI, defined as:

$$DI = 10 log Q$$

For the Mackie 350 used in the field validations tests, the values of DI as a function of frequency are similar to those for the Mackie 450 shown in Table 8.

Table 8. Values of DI for the Mackie 350 Loudspeaker

Frequency (Hz)	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
DI	2	2	3	4	4	5	5	5	5	6	8	9	10	10	9

Alternatively, if the value of DI is not available for a given loudspeaker, it can be calculated from the loudspeaker directivity polars by the method described in Beranek (1986).

The expression for the sound power level, PWL_s, radiated into the room, from Equation (26) is therefore:

$$PWL_S = 10\log\frac{W_S}{W_{ref}} = SPL_x - DI + 20logx + 11$$

where W_{ref} is the reference power of 10^{-12} watt, the reference sound pressure is 2 x 10^{-5} N/m^2, and the distance x is measured in meters. If the measurement distance x is 1 ft (0.33 m) then,

$$PWL_s = SPL_x - DI + 1.4 \quad (28)$$

5.2 VALIDATION OF CALCULATED SOUND POWER CALCULATION

The expression for the source power level, PWL_s, in Equation (28) was derived with assumptions relating to the effect of nearby surfaces on the power output, and the measurement of sound pressure level by a monitoring microphone at a distance of 1 ft from the loudspeaker. Furthermore, it is possible that the directivity index, *DI,* may be affected by placing the loudspeaker close to the room corner—in this case, 5 ft from the apex. To validate Equation (28), the sound power output of the loudspeaker can be calculated by a completely different method that is based on the measurement of reverberant room level generated in the room by the loudspeaker together with a measurement of room absorption. Specifically, Equation (22) from Section 2.4.1 can be rewritten as:

$$PWL_s = SPL_s + 10logA - 6 \quad (29)$$

where PWL_s is the sound power level of the loudspeaker, SPL_s is the resulting reverberant sound level in the room, and A is the room absorption (in mks units). In the field validation tests described in Section 4, the room absorption was measured using a reference sound source with a known sound power output, PWL_r , such that,

$$PWL_r = SPL_r + 10logA - 6 \quad (30)$$

where SPL_r is the resulting reverberant sound level in the room. Combining Equations (29) and (30) provides a separate calculation of the loudspeaker output power from that described in Equation (28), namely:

$$PWL_s = PWL_r + SPL_s - SPL_r \quad (31)$$

The loudspeaker output sound power calculated from Equation (28) can then be validated by comparison to that calculated from Equation (31) for measurements in Houses #3 and #4 in the field validation tests. The comparison of overall levels is presented in Table 9, where it can be seen that the calculation of loudspeaker power based on the sound level measurement at 1 ft and Equation (28) agrees well with that calculated independently using Equation (31).

Table 9. Comparison of Loudspeaker Power Levels Calculated by Different Methods

House	Room	OA* PWL Calculation Method		
		LS Output	RSS	Δ
3	LR	116.2	117.2	-1.0
	BR1	115.9	115.7	0.2
	BR2	115.5	116.1	-0.6
4	BR1	115.6	115.1	0.5
	BR2	116.1	115.6	0.5
	DR	115.5	116.7	-1.2
	LR	115.9	115.5	0.4
Average		115.8	116.0	-0.2

*OA from 100 to 2,500 Hz

The comparisons shown in Table 9 are in terms of the overall (OA) sound power level, where the summation is calculated over the frequency range 100 to 2,500 Hz. Typical examples of the comparison in the spectra of sound power calculated using the two methods are shown in Figure 21, where the values calculated using the loudspeaker output method are labelled “PWL LS @ 1,” and those calculated using the reference sound source are labelled “PWL RSS.”

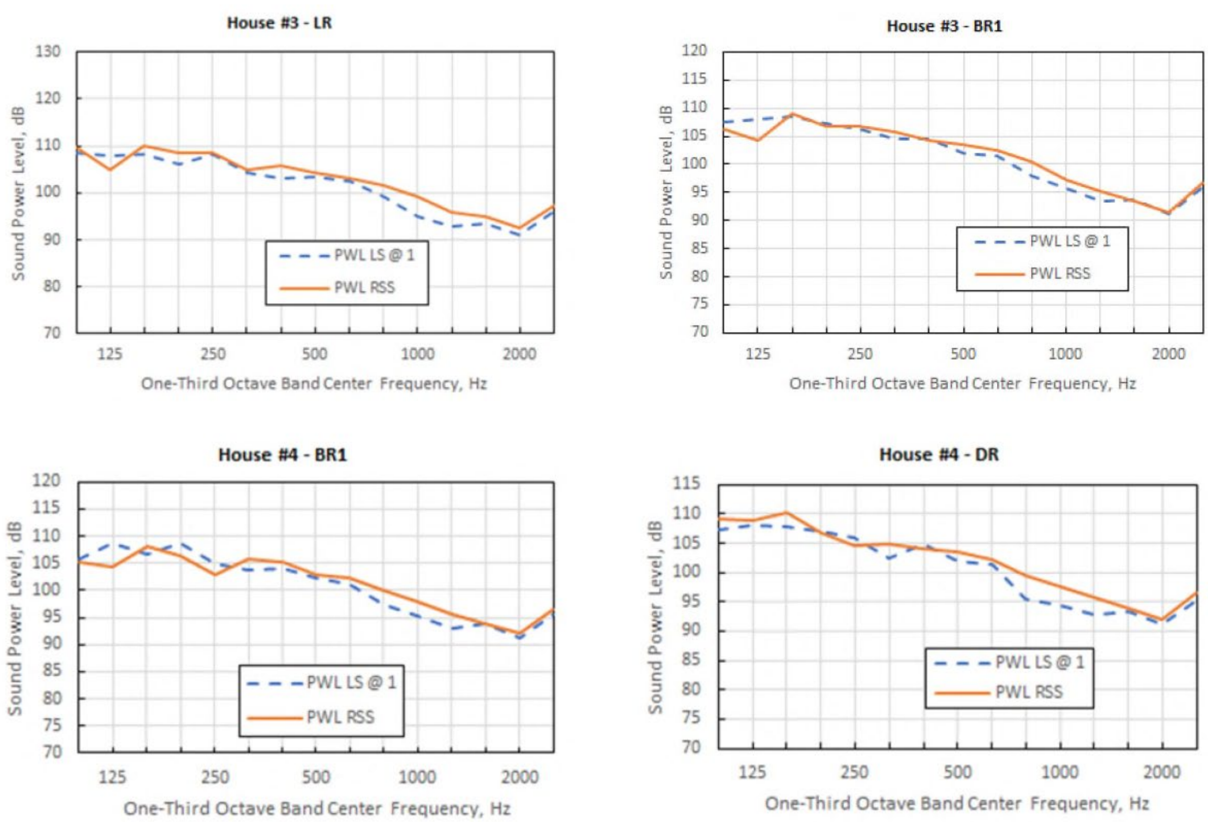


Figure 21. Comparison of Sound Power Spectra as Calculated by Two Different Methods

The two methods are in good agreement over the most important frequency range for calculating NLR, namely 125 to 500 Hz, thus validating Equation (28). However, the loudspeaker output method predicts lower values by a few decibels at higher frequencies.

5.3 CALCULATION OF ALTERNATIVE I-O NOISE REDUCTION

The definition of alternative I-O noise reduction is the difference in sound power generated by the loudspeaker, *Ws*, and the sound power, *Wt*, transmitted to the exterior via the test facade. The sound power, *Ws*, of the noise source, in this case a loudspeaker, is measured in the field by a microphone placed at a distance 1 ft along the main loudspeaker axis. The sound power generated by the loudspeaker can then be calculated using Equation (28).

The sound power, *Wt*, transmitted by the exterior facades of the room is calculated assuming that the exterior sound pressure is measured in the region close to the facade where the radiation is in the form of a plane wave. The expression for the sound power level transmitted, PWL_t, is therefore:

$$PWL_t = 10log\frac{W_t}{W_{ref}} = 10log\left(\frac{p_t^2}{\rho c}S\right) - 10logW_{ref}$$

$$PWL_t = SPL_t + 10logS \qquad (32)$$

where SPL_t is the measured exterior sound pressure level, and S is the total area of the facade in m^2.

The alternative measure of indoor-outdoor noise reduction, NR_{IOAlt}, is then given by combining Equations (31) and (32), thus:

$$NR_{IOAlt} = PWL_s - PWL_t$$

$$NR_{IOAlt} = SPL_x - DI - 20logx - SPL_t - 10logS + 11$$

In the field validation tests, the loudspeaker output was measured at a distance of 0.33 m (1 ft). Thus,

$$NR_{IOAlt} = SPL_{0.33} - DI - SPL_t - 10logS + 1.3 \qquad (33)$$

where S is measured in m^2.

The value of NR_{IOAlt} given by Equation (33) is not necessarily numerically equal to the value of NR_{OI} as the former is based on a different definition of noise reduction. The purpose of this examination is to see whether the two quantities can be related by a constant quantity C, such that:

$$NR_{IOAzt} = SPL_{0.33} - DI - SPL_t - 10logS + C \qquad (34)$$

where the value of C includes the constant 1.3 from Equation (33). Values of NR_{IOAlt} calculated using data from the parametric tests and field validation measurements are shown in Table 10 for values of C from 6 to 9.

Table 10. NLR_{IOAlt} Calculated from the Parametric and Field Validation Test Data

House	Room	O-I NLR	I-O NLR							
			LS at 3 ft				LS at 5 ft			
			C = 6	C = 7	C = 8	C = 9	C = 6	C = 7	C = 8	C = 9
2	Den	24.9	—	—	—	—	24.7	25.7	26.7	27.7
	BR	26.6	—	—	—	—	25.3	26.3	27.3	28.3
3	LR	26.9	24.5	25.5	26.5	27.5	26.3	27.3	28.3	29.3
	BR1	25.3	22.5	23.5	24.5	25.5	23.7	24.7	25.7	26.7
	BR2	23.0	23.9	24.9	25.9	26.9	22.6	23.6	24.6	25.6
	DR/K	22.2	23.1	24.1	25.1	26.1	22.0	23.0	24.0	25.0
4	LR	22.9	22.8	23.8	24.8	25.8	21.9	22.9	23.9	24.9
	BR1	26.0	24.3	25.3	26.3	27.3	25.9	26.9	27.9	28.9
	BR2	24.8	23.0	24.0	25.0	26.0	24.6	25.6	26.6	27.6
	DR	22.3	21.3	22.3	23.3	24.3	22.3	23.3	24.3	25.3

To identify the measurement and calculation method that provides the best agreement between NLR_{OI} and NLR_{IOAlt}, the data in Table 10 is reformatted and presented in Table 11 to compare the values of the two quantities for the different loudspeaker positions, and the value of the constant C.

Table 11. Comparison of the O-I and Alternative I-O NLR Data from the Field Validation Tests

House	Room	O-I NLR	ΔNLR = O-I–I-O NLR								ΔNLR
			LS at 3 ft				LS at 5 ft				LS at 5 ft
			C = 6	C = 7	C = 8	C = 9	C = 6	C = 7	C = 8	C = 9	C = 6.5
2	Den	24.9	—	—	—	—	0.2	-0.8	-1.8	-2.8	-0.3
	BR	26.6	—	—	—	—	1.3	0.3	-0.7	-1.7	0.8
3	LR	26.9	2.4	1.4	0.4	-0.6	0.6	-0.4	-1.4	-2.4	0.1
	BR1	25.3	2.8	1.8	0.8	-0.2	1.6	0.6	-0.4	-1.4	1.1
	BR2	23.0	-0.9	-1.9	-2.9	-3.9	0.4	-0.6	-1.6	-2.6	-0.1
	DR/K	22.2	-0.9	-1.9	-2.9	-3.9	0.2	-0.8	-1.8	-2.8	-0.3
4	LR	22.9	0.1	-0.9	-1.9	-2.9	1.0	0.0	-1.0	-2.0	0.5
	BR1	26.0	1.7	0.7	-0.3	-1.3	0.1	-0.9	-1.9	-2.9	-0.4
	BR2	25.2	1.8	0.8	-0.2	-1.2	0.2	-0.8	-1.8	-2.8	-0.3
	DR	21.3	1.0	0.0	-1.0	-2.0	0.0	-1.0	-2.0	-3.0	-0.5
Average			1.0	0.0	-1.0	-2.0	0.5	-0.5	-1.5	-2.5	0.1
Maximum Range			3.7	3.7	3.7	3.7	1.6	1.6	1.6	1.6	1.6

The alternative method that shows the smallest range of values is that for the loudspeaker positioned 5 ft from the room corner. For this configuration, the optimum value for *C* lies between 6 and 7. Using a value for *C* of 6.5, a comparison of the accuracy of the alternative I-O test method relative to the standard O-I method, is shown in Table 11 and Figure 22.

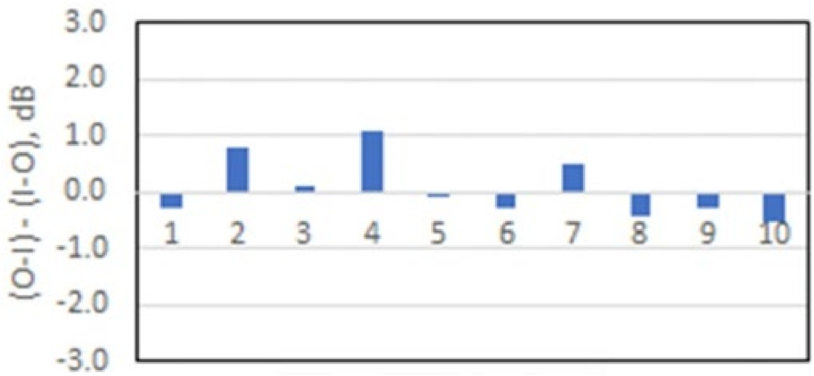


Figure 22. Comparison of the O-I and Alternative I-O Test Methods for $C = 6.5$

The differences between the O-I and alternative I-O measurements for the ten rooms tested are all well within ±1 dB , the average difference being 0.1 dB.

The frequency spectra for the noise reduction measurement by the two methods are shown in Figures 23 and 24 for the 10 rooms tested, with the value of $C = 6.5$. In general, the agreement is close, with small deviations occurring at frequencies greater than 800 Hz, where the loudspeaker output validation also showed lower values shown in Figure 21. Note that the more significant deviation at high frequencies shown in House #2, BR Alt in Figure 23 is the result of high background noise level at the time of the test. The difference in NLR is, however, only 0.8 dB.

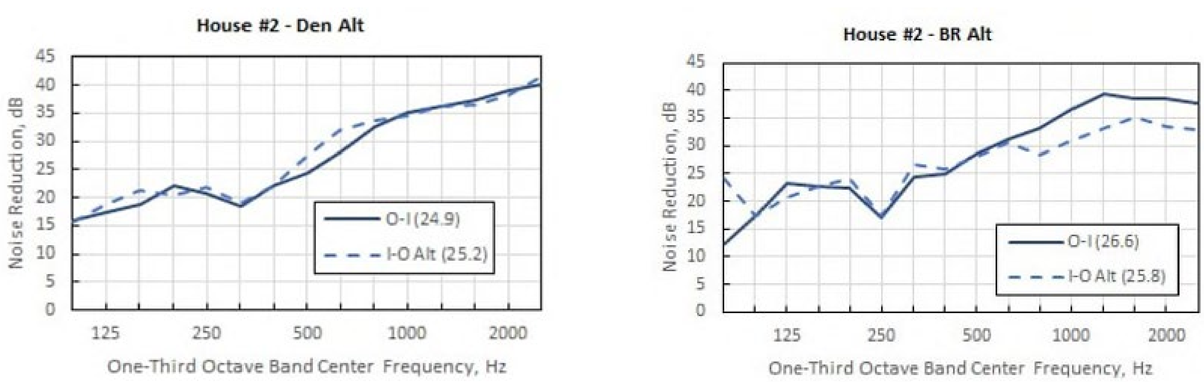


Figure 23. Noise Reduction Frequency Spectrum for House #2 with $C = 6.5$

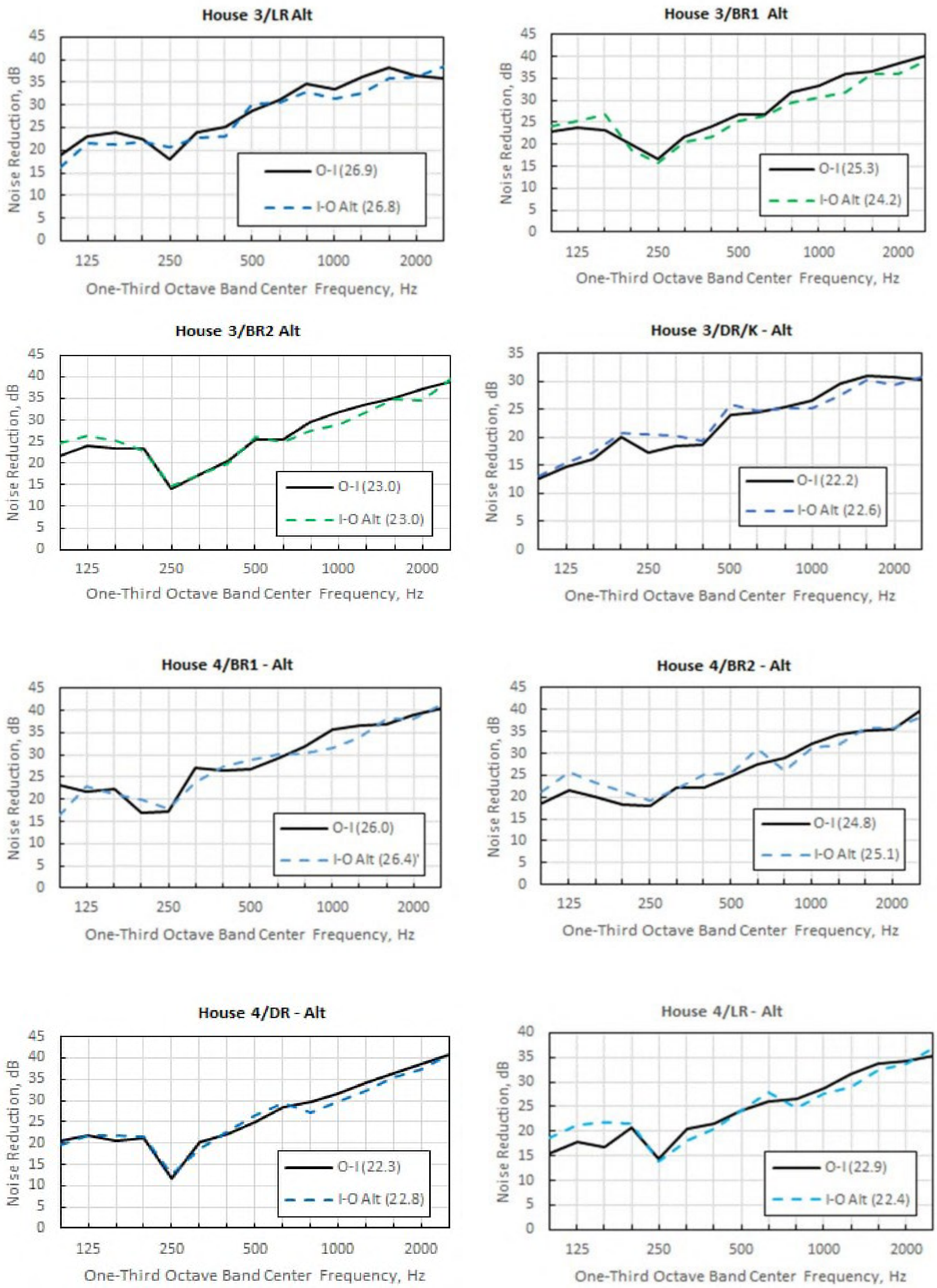


Figure 24. Noise Reduction Frequency Spectrum for Houses #3 and #4 with $C = 6.5$

6. CONCLUSIONS

This report describes the research performed to examine the feasibility of using an indoor-to-outdoor (I-O) testing method, in which a loudspeaker is placed inside the house and the noise reduction measured from inside to outside as a supplemental or alternative measurement approach. This approach eliminates the need for any adjustments to the measurement levels and removes restrictions on the placement of an external loudspeaker. The I-O method also has the advantage that the contribution to the overall noise reduction from different facade elements (i.e., windows and doors) can be directly measured, and an interior loudspeaker would eliminate noise complaints from nearby residents that are often encountered with the outdoor-indoor (O-I) measurements.

- The measurements conducted in 10 rooms of three houses have demonstrated the feasibility of an I-O procedure for the measurement of noise reduction.
- The I-O method that is based on the standard definition of noise reduction, namely the ratio of incident to transmitted sound power, provides data in good agreement with the standard O-I procedure, as described in ARP 6973 (SAE International, 2021), but requires a measurement of room absorption for the data to be comparable to the standard O-I data.
- The alternative I-O method, which is based on a new definition of noise reduction, namely the ratio of the power generated by the loudspeaker to the power transmitted by the test facade, provides data in better agreement with the standard O-I method, and does not require a measurement of room absorption.
- The alternative I-O method is simple and requires only two sound level measurements—one at 1 ft from the loudspeaker, and one by means of a 2D scan conducted 24 in. from the outside of the test facade.
- Background noise is not generally an issue in the measurement of exterior noise with an indoor loudspeaker, although care should be taken to ensure that individual noise events do not occur during the exterior noise scans. Situations may occur where the exterior levels are within 6 dB of the background levels at frequencies above 1,000 Hz, and corrections are required. However, these corrections have a minimal effect on the NLR.
- Further development of the alternative I-O procedure is required before it can be incorporated into ARP 6973; such development should include:
    - Further development of the method for calculating loudspeaker sound power output that simplifies requirements.
    - Additional measurements in houses with special conditions, such as limited outdoor free space, verandas, etc.
    - Verification that the corrections for different house/roof configurations contained in ARP 6973 are appropriate for application with the I-O methodology.

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