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Performance of a noise barrier within an enclosed space

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Abstract

The present study involved experimental, theoretical, and numerical analyses of the insertion loss provided by rigid noise barriers in an enclosed space. The existing classical diffuse-field theory may be unable to predict the actual sound pressure level distribution and barrier insertion loss for indoor applications. Although predictions made by the ray tracing method at high frequencies are reasonably satisfactory, the method is computer-intensive and time-consuming. We propose a new formula that incorporates the effects of diffraction theory and the reflection of sound between room surfaces. Our results indicate that the present formula provides more realistic and practical predictions of the barrier insertion loss than existing approaches.

Keywords: Barrier; Enclosed space; Diffuse-field theory; Ray tracing method

1. Introduction

The provision of aural comfort within an enclosed space is one of the major tasks of the acoustician and noise control engineers. In recent years, noise control achieved by barriers inside enclosed space has become a common measure in indoor environmental protection. Within plant rooms that require airflow for machine cooling, noise generated by the machines can be shielded by barriers. In addition, indoor barriers can be employed to ensure the privacy of speech in open-plan offices. The performance of noise barriers and predictions of their performance are therefore important issues in noise control. In general practice, the diffusion model of reverberant space [1,2] is widely accepted among acoustic engineers when estimating the insertion loss by barrier inside an enclosed space.

The performance of barriers in the free-field condition has been widely studied, in which only ground reflections and those waves that diffract around the edge of the barrier are considered. Based on an analytical solution for wave diffraction by a semi-infinitely long barrier in the free-field condition, Maekawa [3] and Kurze and Anderson [4] derived a simplified chart and expression, respectively, for estimating the insertion loss produced by the barrier. Although many different methods and formulae have been proposed for calculating acoustical diffraction [5–8], those methods that adopt Maekawa's chart [3] and the theory of Kurze and Anderson [4] remain widely used by engineers for outdoor applications, largely because of their simplicity and practicability. Li and Wong [9] provide a comprehensive review of the existing formulae for predicting the performance of a sound barrier in the free field.

In contrast, the behavior of barriers within enclosed spaces has yet to be fully investigated, mainly because the insertion loss by a barrier inside an enclosed space is complicated by the existence of non-uniform reflections from the solid boundaries involved. Existing publications on diffraction and noise reduction by barrier inside an enclosed space can be divided into two broad categories: those that employ classical diffuse-field theory [1,2], and those that use the ray tracing method [10,11] and the image source method [12]. The former approach is limited by the assumption of a uniform distribution of sound energy density, which is seldom fulfilled in reality, particularly in the

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presence of a barrier in a flat room (e.g., an open-plan office). In addition, reverberation theory implicitly assumes a uniform sound-absorption distribution, which is rarely achieved in reality.

The well-known approximation method for this approach was developed by Moreland and Musa [1]. Approximation using the ray tracing method [10,11] is readily applied only in specific cases because of computational difficulties when dealing with irregular enclosures and its low convergence in the presence of highly reflective surfaces [10,11]. Although computer software can help in performing these tedious calculations, phase relationships between sound waves are ignored. Thus, the ray tracing method is only accurate for a random-phase condition and is not applicable in the case of room modes (standing wave), especially for small rooms with high first eigenfrequencies.

Given the shortcomings of previous studies on barrier performance inside enclosures and the fact that the extended development of the theoretical approach has been largely neglected, it is worthwhile to study the performance of a barrier inside an enclosed space using field measurements and to conduct a more in-depth analysis of the problem.

The remainder of the paper is organised as follows. The model of Moreland and Musa [1,2] and the ray tracing methods are reviewed in Section 2. Section 3 describes the development and numerical evaluation of a new equation, while in Section 4 the predictions of the equation are compared with experimental results obtained in a small university classroom.

2. Theoretical background

2.1. Theory of Moreland and Musa [1]

According to the theory of Moreland and Musa [1], the barrier is considered to divide the original room into two rooms that are acoustically coupled by the energy that passes over and around the barrier edges and room surfaces. Based on the diffuse-field theory and energy balance, the sound pressure levels (SPLs) due to a point source within a room before and after erecting a barrier are given as

$$\mathrm{SPL_{Before}} = \mathrm{SWL} + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{S_0\alpha_0}\right) \quad (1)$$

and

$$\mathrm{SPL_{after}} = \mathrm{SWL} + 10\log\left(\frac{QD}{4\pi r^2} + \frac{4K_1K_2}{S(1-K_1K_2)}\right), \quad (2)$$

respectively, where

$$K_1 = \frac{S}{S_1\alpha_1 + S} \quad (3)$$

and

$$K_2 = \frac{S}{S_2\alpha_2 + S}. \quad (4)$$

SWL is the sound power level of the source. Q is the directivity factor of the source, which is 2 for a source located near the floor, 4 for a source at the intersection of two room surfaces, and 8 for a source in the corner of the room. S_0 and S are the total room surface area and the open area between the barrier edges and the room surfaces, respectively. α_0 is the average sound-absorption coefficient of the original room before the installation of the barrier, and r is the distance between the source and receiver without the barrier. The diffraction coefficient, D, is given by

$$D = \sum_i \frac{1}{3 + 10N_i}, \quad (5)$$

where N_i is the Fresnel number for diffraction around the ith edge of the barrier, which can be found using the following formula:

$$N_i = \frac{2\delta_i}{\lambda}, \quad (6)$$

where λ is the wavelength of the sound and δ_i is the difference between the ith diffracted path and the direct path between the source and receiver. $S_1\alpha_1$ and $S_2\alpha_2$ are the sound absorptions of the source and receiver rooms, respectively, after the barrier has been erected. According to Moreland and Musa [1,2], the barrier attenuation, ΔL, which is also known as the insertion loss, is the difference between Eqs. (1) and (2).

Eq. (1) refers to the classical diffuse-field theory of empty enclosed space, while Eq. (2) refers to the summation of the diffracted and diffused sound fields on the receiver side of the partitioned room. Full details of its derivation can be found in Moreland and Musa [1] and are not repeated here. Moreland and Musa [1] assume uniform distributions of sound energy density and sound-absorption before and after insertion of the barrier within each room.

2.2. Ray tracing method

In the ray tracing method, the sound waves are assumed to behave as light rays. Acoustic rays are reflected by solid surfaces, losing energy at each rebound due to surface absorption. The decrease in SPL of each sound ray after n reflections, with a surface absorption coefficient of α_i, is approximately equal to [10]

$$\Delta L_{\mathrm{surf}} = \sum_{i=1}^{n} 10\log(1-\alpha_i). \quad (7)$$

This approach is only valid at higher frequencies. When the rays hit the edge(s) of the barrier, attenuation due to diffraction phenomena can be calculated using the formula of Kurze and Anderson [4]

$$\Delta L_{\mathrm{B}} = 5 + 20\log\left(\frac{\sqrt{2\pi N_i}}{\tanh\sqrt{2\pi N_i}}\right). \quad (8)$$

This represents a conservative estimate of the barrier insertion loss in the free field based on the exact solution for the