CHAPTER 3

Acoustic Shielding: Noise Reduction by Thin and Wide Barriers

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3.1 INTRODUCTION

In controlling noise in the open air, it is very common and important to build a screen or solid fence between a noise source and observers to reduce the noise received. This effect is called 'acoustic shielding'. The acoustic shielding may be achieved not only by a screen but also by many obstacles or barriers such as buildings, earth berms, or terrain that blocks the 'line of sight' from the observer to the source.

Figure 3.1 shows the pattern of a diffracted wave-front caused by a half-plane screen. In the shadow zone of the screen, a cylindrical wave is radiated from the edge of the screen according to the Huygens' Principle, though the incident wave upon the other side of the screen is blocked by the screen. The sound intensity in the shadow zone, however, is not explained by Figure 3.1.

The acoustical design of a barrier is not easy due to the difficulty in the calculation of sound diffraction around the barrier. In order to obtain the sound field, many authors have presented their own theories with various accuracy for various types of sound-wave and shapes of barriers. Theoretical work giving the foundations of this problem have been reviewed in the text by Bowman et al. (1969). There remains the problem of how to simplify and apply the solution to an existing barrier of complicated shape for the purpose of noise control. The rigorous exact solution is generally applicable only for a very simple and pure condition, which is not likely to exist. On the other hand, some approximations are convenient for practical calculations and are suitable for the design of a barrier for noise reduction.

In this chapter, the discussion is limited to a practical process with minimum mathematical analysis, and the results of recent research are conceptually reviewed.
3.2 SIMPLE DESIGN METHOD FOR A NOISE BARRIER

3.2.1 Half-Infinite Thin Screen for a Point Source

For the diffraction of a plane wave by a half-infinite plane in free space, the well-known rigorous solution was given by Sommerfeld (1896). Furthermore, a rigorous solution for a spherical wave in the same condition was given by Macdonald (1915). Although an example of the calculated result of the exact solution is shown later, the well known 'Kirchhoff's diffraction theory', which embodies the basic idea of the Huygens–Fresnel principle (Born and Wolf, 1959), is more suitable in the practice of noise-shielding. The formula is

$$\text{[Att]}_{1/2} = -10 \log_{10} \frac{1}{2} \left[ \left( \frac{1}{2} - C(v) \right)^2 + \left( \frac{1}{2} - S(v) \right)^2 \right] \text{dB}$$  \hspace{1cm} (1)

where $\text{[Att]}_{1/2}$ denotes the diffraction through a half-infinite open space. $C(v)$ and $S(v)$ are Fesnel's Integrals for variable $v$, and

$$v = 2 \cdot \sqrt{\frac{\delta}{\lambda}}$$  \hspace{1cm} (2)

where $\lambda$ is the wavelength of sound, and $\delta$ is the path difference from a source $S$ to an observer $P$ with and without the screen, as shown at the bottom of Figure.
3.2. This theory was originally developed in optics, and a good approximation in optical diffraction does not guarantee the same accuracy in an acoustical problem, because in optics the wave length is very small, whereas the distances from the obstacle to the source and the observer are very long with the opposite conditions existing in acoustics. Figure 3.2 shows the discrepancy between the attenuation values measured by a model experiment (Maekawa, 1968) and the values calculated by Kirchhoff’s Formulae (1) and (2) by converting the variable \( v \) to \( N \) by the relationship

\[
N = \frac{v^2}{2} = \frac{2}{\lambda} \delta
\]

where \( N \) is the so-called ‘Fresnel Number’. Depending on whether \( N < 0 \) or \( N > 0 \), the observer \( P \) lies in the bright zone or in the geometrical shadow, respectively. The scale of the abscissa in Figure 3.2 is adjusted so that the
The experimental curve becomes a straight line. This is done in order for it to be more convenient in using this figure as a design chart, since the experimental curve shows improved approximation of Kirchhoff's theory of diffraction in acoustical problems.

The experimental curve is also expressed by the formula

\[ [\text{Att}]_{1/2} = 10 \log (3 + 20N) \text{ dB}, \quad N > 0 \]  

in the shadow-zone of the screen (Kurze, 1974). This formula is suitable for the design of a noise-barrier with the aid of a computer.

### 3.2.2 Large Extended Noise Sources

It is a more difficult problem to obtain a solution of sound diffraction theoretically with a large source, because the wave-front from the large source cannot be expressed exactly. There is a conventional method, however, if the large source can be replaced by one or more point sources. When noises are emitted incoherently from virtual point sources, the sound energy received from each point source, which can be obtained as mentioned above, should be summed up at the receiving point. This conventional method has been verified by many case-studies.

For the special case of a street or a highway, noise is often treated as an incoherent line-source. The performance of a barrier against highway noise should be considered with a line-source parallel to the edge of the barrier. The results of the theoretical computations and also of the experimental studies are shown by a dashed-curve in Figure 3.2. It is more useful in practice to estimate the attenuation by a barrier for road traffic noise.

### 3.2.3 Finite-Size Screen

There is no such thing as an infinitely long screen but only finite-size screens of limited length. In order to obtain the sound level in the shadow-zone of such a screen, all contributions from the open surface, diffracted sound not only over the top edge but also over the side-edge of the end of the screen, must be integrated at the receiving point.

In the simplest case, if the length of a half-infinite screen is limited at one end, the open surface should be divided into two zones [A] and [B] as shown in Figure 3.3. Zone [A] is a half-infinite empty plane, and [B] is a quarter-infinite one. The contribution of zone [A], denoted by \( L_A \), is obtained by the method mentioned above, using the path difference \( \delta_1 = (\overline{SO_1} + \overline{O_1P} - \overline{SP}) \) and the Fresnel number \( N_1 = \delta_1 \cdot 2/\lambda \). The value of attenuation denoted by \([N_1]\) is given in Figure 3.2. Then \( L_A = -[N_1] \) dB. In order to obtain the contribution of zone [B], denoted by \( L_B \), after calculating \( N_2 \) in the path \( S-O_2-P \), the value of attenuation \([N_2]\) is given
in Figure 3.2. The limiting effect caused by the edge of $xx'$, denoted by $[-N_1]$, is also given in Figure 3.2. Then $L_B = - \{ [N_2] + [-N_1] \}$ dB.

The sound level at $P$ is obtained by summing $L_A$ and $L_B$.

When the screen has another end, the contribution of another open surface of a quarter-infinite empty plane should be added to the sound level at $P$ in the same way as mentioned above.

### 3.2.4 Simple Estimation for a Wide Barrier

According to much experimental data, the effect of the thickness of a screen should be negligible as long as the thickness is smaller than the wavelength. However, there are many occasions when the thickness of the barrier, such as that of a building, must be considered.

The simplest way is to find the effect of thickness $b$ of the wide barrier, $[ET]_b$, which must be added to the value of attenuation by an imaginary thin, half infinite screen shown in Figure 3.4. Though the result of theoretical computation shows the resonance effect related to the thickness $b$, with reasonable approximation, the effect of thickness for a noise having a considerable bandwidth is presented by

$$n[ET]_b = K \cdot \log_{10} kb$$

where $K$ is the value given by a single chart of Figure 3.5, and $k = 2\pi/\lambda$ (Fujiwara, et al., 1977).
3.3 APPLICATION OF EXACT SOLUTIONS OF SOUND DIFFRACTION

3.3.1 Half-Infinite Thin Screen

The rigorous solution for spherical wave diffraction with a half-infinite thin screen was given by H. M. Macdonald (1915) and several other authors.

The theoretical solutions for the sound field at the receiving point P are generally expressed by Equation (6) as the sum of two terms:

\[ U_{SP} = \phi_{SP} + \phi_{S'}P \]  

(6)

where the first and the second term express the diffracted sound fields from the real source S, and from the image source S' in the screen, respectively, assuming perfect reflection at the surface of the screen.

In Figure 3.6, an example of the numerical calculation of this rigorous solution is compared with the experimental results and also with the approximate values obtained in Figure 3.2 (Kawai et al., 1977). It can be seen that the exact solution can give the sound-pressure distribution not only in the shadow zone of the screen but in the bright zone of the sound source.

The calculation of the solution is very complicated, but some good approximations suitable for numerical computation are also given in the literature (Kawai et al., 1977).

3.3.2 Infinite-Long Wide Barrier

When the thickness of a barrier is large, it generally has two or more straight edges, as in the case of a building or an earthen bank. Multiple-edge diffractions occur at every edge of the barrier. An exact solution of this case was given based on the single wedge diffraction solution and on concepts
inherent in Keller's geometrical theory of diffractions (Pierce, 1974). Though the calculation is very comprehensive, several approximations giving good results are presented for various shapes of barriers. Figure 3.7 shows an example of the calculated results compared to values measured by using an experimental model (Kawai, 1980).

**3.4 EFFECT OF SURFACE ABSORPTION OF THE BARRIER**

The surface condition of the barrier mentioned above is regarded as rigid and assumed perfect reflection. However, walls or screens heavily treated with absorptive materials are widely used as noise barriers.

For the effect of the surface absorption of a half infinite screen, the second term of Equation (6), which expresses the sound field by reflection from the barrier surface, must be multiplied by the reflection coefficient $R$, of the surface. Strictly speaking, the reflection coefficient must be the one for a
spherical sound wave as mentioned in the next section, but it is often approximated, by the coefficient for a plane wave as practical convenience. By means of further simplification in neglecting the imaginary part of the complex acoustic reflection coefficient of the surface, the result of the theoretical derivation is given by Figure 3.8 (Fujiwara et al., 1977). From the practical point of view, we can quickly estimate the effect of the surface absorption only by adding the value of Figure 3.8 to the values of attenuation obtained by the method mentioned above.

### 3.5 EFFECT OF SOUND REFLECTION FROM THE GROUND

Most of the barriers are built on the ground, and we must consider the effect of sound reflection from the ground as well as the surface of the barrier. In Figure 3.9, assuming specular reflections at the surfaces of the screen and the ground, $S'$, $T$ and $T'$ are the images of the point source $S$, and $P'$ is the image of the observer $P$.

#### 3.5.1 Simple Design Method for a Barrier on the Ground

As the simplest treatment of those sound reflections, the source side images $T$,
T' and S' are neglected, and instead, the sound-level at the top of the screen, including the sound reflections from those images, is selected as the reference value of the sound level in the shadow-zone of the barrier. In this way, we can ignore not only the directivity of the source but also the reflectivity of the ground. Then at the receiver's side, the ground reflection is calculated by means of the same method for the image point P', assuming perfect specular reflection on the ground. This approximation can be useful for the practice of designing a noise screen erected on hard ground.

### 3.5.2 Insertion Loss of a Barrier on the Ground

Strictly speaking, the total sound field at the receiving point P consists of eight fields as follows:

\[
U = \phi_{SP} + \phi_{S'P} + \phi_{TP} + \phi_{T'P} + \phi_{SP'} + \phi_{S'P'} + \phi_{TP'} + \phi_{T'P'}
\]

where each term is defined similarly to Equation (6) according to their subscript. Furthermore, the sound reflectivity should be considered at the surface of the ground as well as at the screen.
When the screen has perfect reflection, we can apply the rigorous solution of Equation (6). Then Equation (7) becomes

\[ U = U_{SP} + U_{TP} + U_{SP'} + U_{TP'} \]  

(8)
The total sound-field consists of the four fields in Equation (8). Also, the sound reflectivity of the ground must be taken into account.

The coefficient of ground reflection $Q$ for a spherical sound wave is presented as follows:

$$Q = R + (1 - R)F$$  \hfill (9)$$

where $R$ is the reflection coefficient for a plane wave at the ground surface, and $F$ is a complicated mathematical function of the distance from $S$ to $P$, of the grazing angle $\psi$ and also of the surface impedance $Z_2$, as shown at the top of Figure 3.10.

Figure 3.10  Excess attenuation calculated for propagation from a point source over mown grass for $h_s = 1.8 \text{ m}$, $h_p = 1.5 \text{ m}$, and the distances of propagation $d$ indicated. The excess attenuation is relative to that for the point source placed on a perfectly hard surface. (Piercy et al., 1977)

The curves in Figure 3.10 show excess attenuations calculated for propagation over mown grass in the configuration shown at the top of the figure. These results show good agreement with field measurements. It is clear that the excess attenuation grows unbelievably by distance at some frequency with no barrier.
When a screen is erected on the ground, the effect of the screen on noise reduction is defined as ‘Insertion Loss’, i.e., the difference in sound-pressure levels caused by the same source with and without the barrier at the observer P. It is possible for the excess attenuation caused by a barrier on the ground to be smaller than that caused only by the ground without the barrier, since it is possible for the latter to be very significant as shown in Figure 3.10. It disappears after the erection of the barrier.

Figure 13.11 shows an example of the insertion-loss of a theoretical calculation compared with the simple approximation mentioned at the beginning of this Section (Isei et al., 1980).

![Figure 3.11](image)

Figure 3.11 Insertion loss of a barrier on the ground for the geometrical configuration shown at the top of the figure. The line source is above a hard surface, and the ground on the receiver side of the barrier is hard for Curve 1 and 2, but soft, grass-covered, for Curve 3. Curve 2 is the prediction from Figure 3.2, though the others are calculated by exact solutions (Isei et al., 1977)

### 3.6 CALCULATION OF SOUND FIELDS BY INTEGRAL EQUATION METHODS

The problem of determining reflected or diffracted sound-fields has often been treated by using Helmholtz-Kirchhoff’s integral formula for objects of simple shapes. The mathematical solutions, however, were not suitable for practical application.

Recently, new techniques for numerical calculations of the integral equation solutions have been developed as derived from Green’s formula. The numerical results are found to be in very good agreement with the measured values as shown in Figure 3.12 (Terai, 1980).
The advantages of this method are related to its possible application to all barriers of any complex shape, and for all rigid or absorptive materials. But, it is necessary to consider how many divisions in the given barrier-shape are suitable for calculation, and how to treat the surface absorption characteristics of the material and of the ground.

### 3.7 REFERENCES
