A chart for estimating the distance attenuation of flanking sound passing through open windows in the exterior wall of adjoining rooms and its experimental verification

Yasuhito Kawai a,*, Tadao Fukuyama b, Yuzo Tsuchiya b

a Department of Architecture, Faculty of Engineering, Kansai University, Japan
b Technical Research Institute, Toda Corporation, Japan

Received 22 November 2003; received in revised form 9 March 2004; accepted 2 April 2004
Available online 19 June 2004

Abstract

Sound transmission between adjoining rooms is often influenced by flanking sound passing through open windows placed in the exterior wall of the two rooms. It is important to predict such flanking sound propagation when considering the sound insulation between the adjoining rooms. In this paper, a chart for estimating the distance attenuation of the flanking sound, which is obtained from analysis using the boundary integral equation method, is first provided. Next, 1:10 scale model experiments are carried out. The experimental results are in good agreement with the chart, the effectiveness of the chart thus being verified.

Keywords: Flanking sound; Open window; Adjoining room; Transmission rate; Boundary integral equation; BEM; Image method

1. Introduction

Sound transmission between adjoining rooms is often influenced by flanking sound passing through open windows in the shared exterior wall of the rooms. It is thought that such flanking sound might be more influential than sound transmitted through
the partition wall, especially in the summer when the windows are frequently open. In order to predict flanking sound propagation, one of the authors constructed a chart based on two-dimensional analysis using boundary integral equations [1]. It is more important, however, to predict three-dimensional propagation. In this paper, a chart for predicting flanking sound obtained from three-dimensional analysis using boundary integral equations is presented and its effectiveness verified by 1:10 scale model experiments.

2. Formulation

Let a source room, which includes an omnidirectional point sound source, be adjoined to a receiving room, as shown in Fig. 1. Each room has an aperture, \( A_1 \) or \( A_2 \), in its exterior wall, \( S_1 \) or \( S_2 \). The thickness of the exterior wall is considered to be acoustically rigid and thin enough for the wavelength. The ‘flanking sound’ means here the sound which is emitted from the aperture \( A_1 \) propagated in the exterior space \( \Omega_0 \) and entering through the aperture \( A_2 \) into the receiving room. For simplicity’s sake, in this analysis, the source room and the receiving room are assumed to be semi-infinite. Though the two rooms are illustrated as quarter-infinite spaces in Fig. 1, this assumption means that the surfaces of the partition wall between them are both perfectly absorbent. This assumption also presumes a one-directional sound incidence on the aperture \( A_1 \) and no reradiation from the aperture \( A_2 \). With this assumption, the flanking sound, which is derived from the energy emitted from aperture \( A_1 \) and that entering through the aperture \( A_2 \), can be precisely estimated.

Let us consider an infinitely large rigid flat surface, in two parts of which are apertures \( A_1 \) and \( A_2 \). Also, let a semi-infinite space \( \Omega_0 \) bounded by the infinitely large semi-sphere \( \Sigma \), the rigid surfaces \( S_1 \) and \( S_2 \), and the apertures \( A_1 \) and \( A_2 \) include a receiving point \( P \), and let \( P_1 \) be the image point of \( P \) with respect to the surfaces \( S_1 \), \( S_2 \), \( A_1 \) and \( A_2 \) (see Fig. 2).

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Propagation of flanking sound passing through open windows.}
\end{figure}
In order to derive an integral formula with respect to the space $\Omega_0$, we will use

$$G(P, Q) = \frac{\exp(ikr)}{4\pi r} + \frac{\exp(irk_i)}{4\pi r_i},$$

as a fundamental solution, in which the image point $P_i$ is taken into account. Here, $r = PQ$ and $r_i = P_iQ$. The time factor $\exp(\frac{-iot}{\epsilon})$ is omitted throughout this paper. We

Fig. 2. Derivation of integral formula with respect to exterior space: $\Omega_0$ semi-infinite space bounded by rigid walls $S_1, S_2$, apertures $A_1, A_2$, and infinitely large semi-sphere $\Sigma$; $n$ normal vector; $P$ receiving point; $P_i$ the image of $P$ with respect to $S_1, S_2, A_1, A_2$; $\epsilon$ small sphere of center $P$ and radius $\epsilon$.

Fig. 3. Transmission rate TR in decibels of flanking sound varying with distance between the midpoints of the apertures of the source and receiving rooms.
apply Green’s theorem to the space \( \Omega_0 - \sigma \), where \( \sigma \) is a small sphere of center \( P \) with radius \( \epsilon \). Taking into consideration (1) the normal component of particle velocity vanishes throughout \( S_1 \) and \( S_2 \), (2) \( \partial G / \partial n = 0 \) throughout \( S_1, S_2, A_1 \) and \( A_2 \), and (3) Sommerfeld’s radiation condition [2], we can obtain

\[
\Phi(P) = -\frac{1}{2\pi} \int_{A_1+A_2} \frac{\partial \Phi(Q)}{\partial n} \exp(ikr) \frac{1}{r} \, dS, \quad (P \in \Omega_0, A_1, A_2, S_1, S_2), \tag{2}
\]

where \( \Phi(P) \) denotes velocity potential at \( P \) and \( n \) the inward drawn normal. Eq. (2) is valid when \( P \) is located on \( S_1, S_2, A_1 \) or \( A_2 \) (i.e., \( P = P_i \)), since

\[
\lim_{\epsilon \to 0} \int_{\partial \sigma/2} dS = -\Phi(P), \quad (P \in S_1, S_2, A_1, A_2) \tag{3}
\]

As for the space \( \Omega_1 \), considering the point source is located within it and Eq. (1) is used as the fundamental solution, we have

Fig. 4. Outline figure of the 1:10 scale model used in experiments.
\[ \Phi(P) = \Phi_D(P) + \Phi_D(P_i) + \frac{1}{2\pi} \int_{A_1} \frac{\partial \Phi(Q)}{\partial n} \frac{\exp(ikr)}{r} \, dS, \quad (P \in \Omega_1, A_1, S_1), \]  

(3)

where \( \Phi_D \) denotes a direct sound and \( n \) the outward drawn normal. The point \( P_i \) also denotes the image point of \( P \in \Omega_1 \) with respect to \( S_1 \) and \( A_1 \).

Considering that no source is located, we can also obtain an integral formula for the space \( \Omega_2 \) in the same way: i.e.

\[ \Phi(P) = \frac{1}{2\pi} \int_{A_2} \frac{\partial \Phi(Q)}{\partial n} \frac{\exp(ikr)}{r} \, dS, \quad (P \in \Omega_2, A_2, S_2). \]  

(4)

When \( P \) is located on \( A_1 \) or \( A_2 \), then Eqs. (2)–(4) are integral equations with an unknown function \( \partial \Phi/\partial n \) on \( A_1 \) and \( A_2 \). When \( P \) is located on \( A_1 \), subtracting the difference between Eqs. (2) and (3) yields

\[ \frac{1}{\pi} \int_{A_1} \frac{\partial \Phi(Q)}{\partial n} \frac{\exp(ikr)}{r} \, dS + \frac{1}{2\pi} \int_{A_2} \frac{\partial \Phi(Q)}{\partial n} \frac{\exp(ikr)}{r} \, dS = -2\Phi_D(P), \quad (P \in A_1). \]  

(5)

### Table 1

Distances between the midpoints of windows in the scale model

<table>
<thead>
<tr>
<th>Window width (mm)</th>
<th>Distance between the midpoints of windows (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Extreme approach</td>
</tr>
<tr>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>400</td>
<td>500</td>
</tr>
</tbody>
</table>

Fig. 5. Arrangement for model experiments. Sound pressure levels at five points denoted by dots in each room are measured (see also side view of Fig. 4).
Also, when $P$ is located on $A_2$, subtracting the difference between Eqs. (2) and (4) yields

$$
\frac{1}{2\pi} \int_{A_1} \frac{\partial \Phi(Q)}{\partial n} \exp(ikr) \, dS + \frac{1}{\pi} \int_{A_2} \frac{\partial \Phi(Q)}{\partial n} \exp(ikr) \, dS = 0, \quad (P \in A_2). \tag{6}
$$

Solving the simultaneous integral Eqs. (5) and (6), we can obtain $\partial \Phi/\partial n$ on $A_1$ and $A_2$, which gives the velocity potential $U$ in $\Omega_0$, $\Omega_1$ and $\Omega_2$ by substituting it into Eqs. (2)–(4), respectively.

The energy $I_1$ emitted from the aperture $A_1$ and the energy $I_2$ entering through the aperture $A_2$ can be obtained by the potential $\Phi$ and $\partial \Phi/\partial n$ on $A_1$ and $A_2$ using the following equations:

$$
\begin{align*}
\rho = -\omega \rho \Phi, \\
v = -\frac{\partial \Phi}{\partial n},
\end{align*}
$$

and

Fig. 6. Comparison of the radiation directional characteristics: (a) when diffusion objects are suspended from the ceiling (see side view of Fig. 4), and (b) when in addition to the characteristics of case (a), columns made of wood and absorbent expanded polystyrene are installed near three side walls (see Fig. 5). The results are converted to that of real scale.
\begin{align}
I_1 &= \int_{A_1} \frac{1}{2} (p v^* + p^* v) \, dS, \tag{8} \\
I_2 &= \int_{A_2} \frac{1}{2} (p v^* + p^* v) \, dS, \tag{9}
\end{align}

where \( p^* \) and \( v^* \) are complex conjugates of sound pressure \( p \) and particle velocity \( v \), respectively [4].

The transmission rate \( TR \) (in dB) of the flanking sound is obtained by
\[
TR = 10 \log_{10} \frac{I_2}{I_1}. \tag{10}
\]

3. A chart of distance attenuation

For purposes of noise control, it is useful to know the transmission rate of flanking sound under a condition of 1 octave band noise random incidence. In order to simulate the above condition, numerical calculations are carried out for 825 plane waves that are incident on the aperture \( A_1 \) from all directions at regular solid angle intervals and for six frequencies taken in the octave band. The energies of both the emitted wave from \( A_1 \) and of the incoming one are calculated for each condition and summed up separately. The transmission rate under conditions of random incidence can thus be obtained by using the resultant values.

Fig. 3 shows a chart of the distance attenuation of flanking sound calculated using the above-mentioned method when the dimension of both apertures is \( 1 \times 1 \) m\(^2\). The abscissa in this chart denotes the distance between the midpoints of the apertures.

![Fig. 7. Block diagram of measurement apparatus.](image-url)
We can see that the transmission rate reduces by \( \approx 6 \text{ dB} \) for every doubling of distance. If the apertures have dimensions \( S_{a1} \) and \( S_{a2} \), on the basis of the diffuse sound field assumption, we have

\[
L_1 - L_2 = \text{TR} + 10 \log_{10} \frac{A}{S_{a1}S_{a2}},
\]

(11)

Fig. 8. Differences between sound pressure levels in the source and receiving rooms with: (a) width of apertures 200 mm, (b) width of apertures 300 mm, and (c) width of apertures 400 mm. The averaged level for five points in each room is used to obtain the level differences.
where $A$ denotes the absorption power of the receiving room, and $L_1$ and $L_2$ are energy density levels in the source room and the receiving room, respectively.

4. Scale model experiment

4.1. Outline of experiments

As shown in Fig. 4, 1:10 scale model rooms are made from vinyl chloride plate 10 mm thick. Each room has an aperture whose dimensions can be changed between $200 \times 200$, $300 \times 200$ and $400 \times 200$ mm$^2$. The distances between the midpoints of the apertures in the above three cases are shown in Table 1. The receiving room is

![Fig. 9. Comparison of experimental with theoretical values.](image-url)
isolated from the source room in order not to be excited. In the experiment for distance attenuation, the receiving room is moved, keeping the source room fixed. Model experiments are carried out in a chamber whose peripheral walls are covered with triple absorbent layers. The measured inverse square law of sound pressure level in this chamber coming from the point source is shown to be satisfactory.

![Diagram](image)

**Fig. 10.** Measurement of the radiation directional characteristics when the setting of tweeters is changed. Dots in front of the aperture denote measuring points.

![Diagram](image)

**Fig. 11.** Comparison of the radiation directional characteristics of (a) the arrangement shown in Fig. 5, and (b) the arrangement shown in Fig. 10 (250 Hz).
In order to simulate the diffuse sound field in the model source room, the following two cases are investigated: (1) diffusion objects made from plastic board are suspended (see side view of Fig. 4), and (2) in addition, columns made of wood and absorbent expanded polystyrene are installed near three side walls as shown in Fig. 5. The radiation directional characteristics from the source room for the two cases are indicated in Fig. 6. As the result for case (2) is better than that for case (1), we adopt the case (2) setting. Columns are also installed to the model receiving room (see also Fig. 5). The measurements also show that the deviation of the sound pressure levels in the source room is relatively small under this arrangement. A block diagram of our measurement apparatus is given in Fig. 7. Noise source signals of 1 octave band from 500 to 40 kHz are generated from four tweeters. Three 1/4-in. microphones are used for receivers and 1/3 octave band levels are measured using an FFT spectrum analyzer.

4.2. Results of experiments

All the results obtained from model experiments are converted to those of real scale. Fig. 8(a)–(c) show the differences between sound pressure levels (measured for 1/3 octave bands) in the source room and the receiving room when both the aperture widths are 200, 300 and 400 mm, respectively. Though sound pressure levels are expected to increase monotonically with increasing frequency, they rise at about 250 Hz in all cases. After the results shown in Fig. 8(a)–(c) are converted to those of 1 octave band, the transmission rates are calculated using Eq. (11) and compared with

![Graph](image-url)
the distance attenuation chart, as shown in Fig. 9(a)–(c). As uneven sound pressure level distribution is expected in the source or the receiving room mainly due to the existence of the aperture, the averaged level for five points in each room are used for energy density level $L_1$ or $L_2$ (see Fig. 5). We can see that the experimental values are in good agreement with the theoretical values, within $\pm 2$ dB for all octave bands except one band at the center frequency 250 Hz.

The reason of the discrepancy at the 250 Hz band is probably due to bad radiation directional characteristics from the aperture of the source room as shown in Fig. 11(a). If the setting of tweeters is changed as shown in Fig. 10, better radiation directional characteristics is obtained (see Fig. 11(b)). Under this setting the discrepancy between the experimental and theoretical values at the 250 Hz band is improved as shown in Fig. 12.

5. Conclusion

The effectiveness of the chart to predict flanking sound obtained from analysis using boundary integral equations was verified experimentally. As the chart was derived under a condition of 1 octave band noise random incidence, it should prove useful when diffuse sound fields in the source and receiving rooms are approximated.

References