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SIMPLE ESTIMATION METHODS FOR NOISE REDUCTION BY VARIOUSLY SHAPED BARRIERS

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Simple estimation methods for various noise barriers are reviewed from the practical point of view of noise control. Some simple charts for the barriers of various bodies are found by experimental and theoretical studies. It has been clear that the integral equation method is useful to predict the noise reduction by a semi-transparent barrier.

1. Introduction

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 source to the observer. But the acoustical design of a barrier is not very easy due to the difficulty in the calculation of sound diffraction around the barrier. In this paper simple estimation methods for various noise barriers are reviewed from the practical point of view. Although the rigorous solutions of sound diffraction are presented by many authors, the simple and pure conditions which are needed for the rigorous solutions can scarcely be found in practice in citu. Therefore rough estimation methods are still useful in the practice of noise control.

2. Half-infinite thin screen for a point source

When a half infinite plane screen exists between a point source S and a receiver, P in free field, the well known chart in Fig. 1 is the simplest and most reliable method to obtain noise attenuation with reasonable accuracy, though the results generally have values lower by a few dB than those KIRCHHOFF'S approximate theory as shown in the Fig. 1.

In the region of $N \geqslant 1$, the attenuation is expressed by

$$[Att]_{1/2} = 10 \log (20\, N) \quad [\text{dB}]. \tag{1}$$

It is proved that this expression is the first term of an asymptotic formula derived from the exact theory of diffraction by Keller. 2)

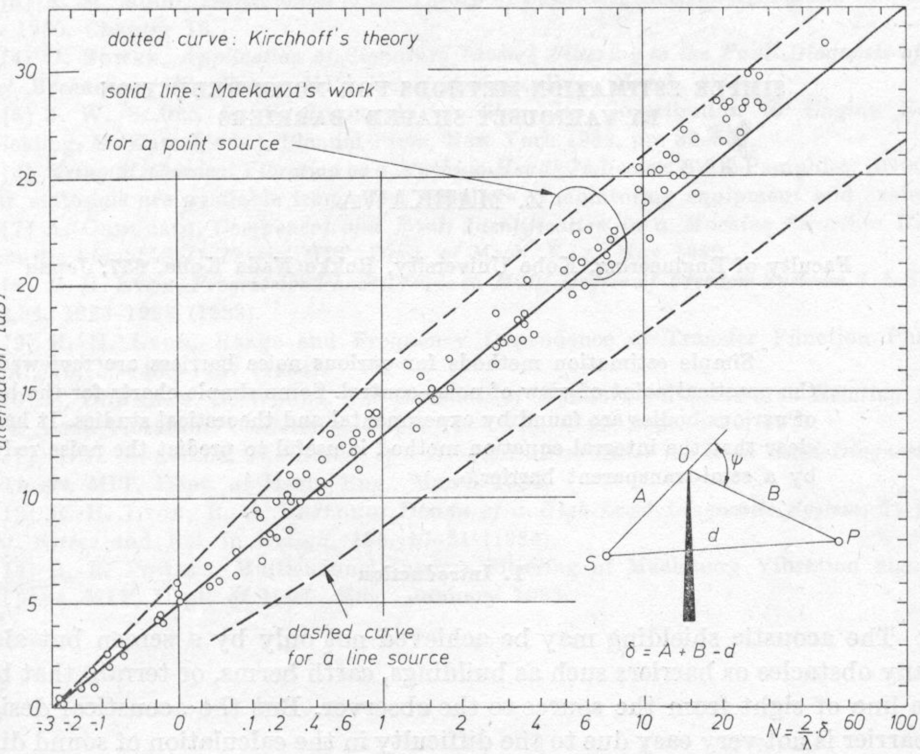

Fig. 1. Sound attenuation by a semi-infinite screen in free space. Horizontal scale, logarithmic scale in the region of $N > 1$, adjusted so that the experimental curve becomes a straight solid line in the region of $N < 1$. Depending on whether $N < 0$ or $N > 0$, the receiving point P lies in the illuminated region or in the geometrical shadow, respectively. Attenuation is relative to propagation in free space. o-experimental values measured by pulsed tone

For the entire range of N, Formula (2)

$$[Att]_{1/2} = 5 + 20 \log \frac{\sqrt{2\pi |N|}}{\tanh \sqrt{2\pi |N|}} \quad [\text{dB}] \tag{2}$$

is convenient for calculation with the aid of a computer, though it has a small discrepancy, within 1.5 dB only in the range $N < 1$. 3)

The variable N is calculated with the value of δ, the path length difference, which may be simply obtained by geometry.

3. Simple estimation of the effect of ground reflection

When the long screen WO is erected on the ground between S and P, and distances between them are not as long as shown in Fig. 2, the sound pressure level at P can be predicted according to the following process:

(1) The sound level L_0 at the top of the screen is asigned as the reference value of the sound level at any point in the shadow zone of the screen. By this procedure both the directivity of the noise source and the reflection from the ground between S and the screen can be at a certain approximation neglected.

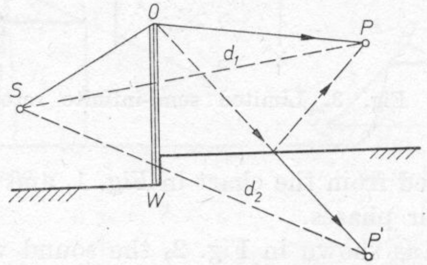

Fig. 2. Section of the long wall between a sound source S and a receiving point P

(2) The effect of ground reflection is calculated by the summation of the sound energy received at P and P', the image of receiver P, assuming perfect specular reflection on the ground and neglecting their phases. If the summation is expressed by L_3 in the level of attenuation, the sound level at P with the screen is obtained by

$$L = \left(L_0 - 20 \log \frac{d_1}{\overline{SO}}\right) - L_3 \quad [\mathrm{dB}]. \tag{3}$$

(3) The shielding effect of the screen, however, must be obtained by the expression $(L_p - L)$ dB, where L is the value calculated by the method mentioned above and L_p is the measured value of the sound level at point P when the wall is absent. We call it the insertion loss of the screen, and it is variable owing to both the directivity of the sound source and the reflectivity of the ground.

4. Attenuation by a finite-size screen

In general, even if a wall or screen has any shape, the sound level in the shadow zone of the screen must be integrated from all the contributions from the open surface.

In the simple case where the length of the semi-infinite screen in free space is limited on both sides, as shown in Fig. 3, the open surface should be divided into three zones [A], [B], and [C]. Zone [A] is then a half-infinite empty plane, and both [B] and [C] are quarter-infinite zones.

The contribution of a half-infinite open surface, of course, can be obtained by the chart in Fig. 1. The contribution of a quarter-infinite open surface can be obtained by summing the two attenuation values of semi-infinite screens, according to the Fresnel-Kirchhoff's diffraction theory [1]. These values, of co-

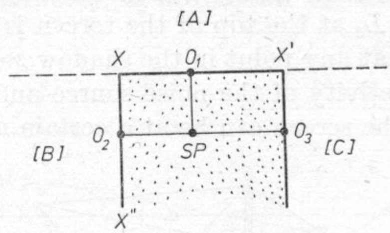

Fig. 3. Limited semi-infinite screen

urse, are easily obtained from the chart in Fig. 1, and added together with its energy neglecting their phases.

In the same way as shown in Fig. 2, the sound wave reflected from the ground is calculated at the point P', the image of P as shown in Fig. 4, conside-

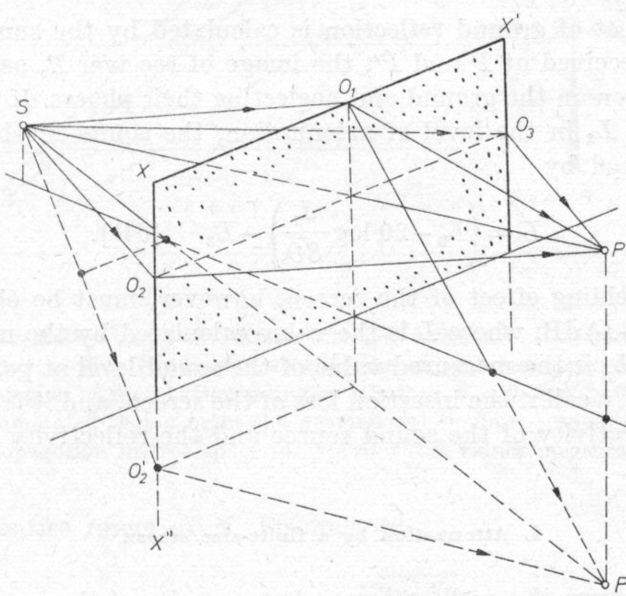

Fig. 4. Propagation paths around the finite size screen

ring the specular reflection of the ground. The sound energy at the receiving point P and that at the image P' should then be added together.

When a thin screen has a complex multilateral shape, the sound level in the shadow zone of it can be obtained by the same principle, as you can find in the literature [4].

5. Simple estimation for barriers of various bodies

Until now, the screen was assumed to have zero thickness. The barriers, however, have their own bodies as shown in Fig. 5. To calculate the noise reduction in the first approximation, we use the chart in Fig. 1 with the value of the path difference,

$$\delta = \overline{SO}+\overline{OP}-\overline{SP} \quad \text{or} \quad \delta = \overline{SX}+\overline{XY}+\overline{YP}-\overline{SP}.$$

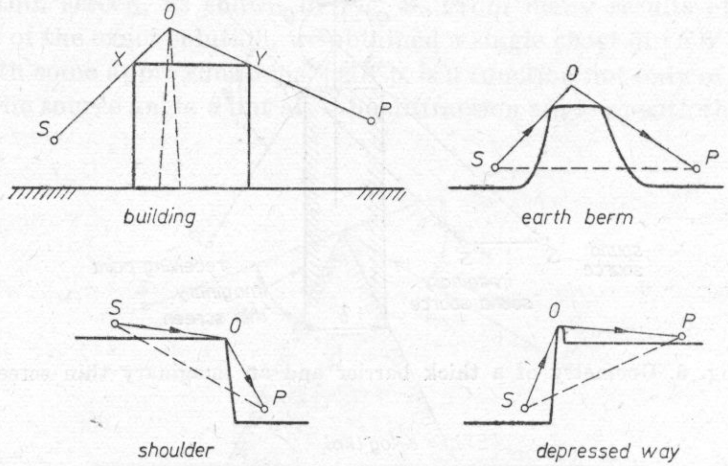

Fig. 5. Noise reduction can be obtained by Fig. 1 by using the path difference of each case

This is the simplest way, though there are more accurate methods as follows:

(*A*) *Effect of the thickness of a screen* [5].

According to many experimental data, the effect of the thickness of a screen should be negligible as long as the thickness is smaller than the wave length. A thick plate or wide barrier has two edges which increase the noise reduction by double diffractions.

The attenuation of a band noise by a thick barrier $_n[Att]_b$ is assumed to be composed of the attenuation by an imaginary thin screen $_n[Att]_0$ and the effect of the thickness of the barrier $_n[ET]_b$ expressed by

$$_n[Att]_b = {}_n[Att]_0 + {}_n[ET]_b \quad [\text{dB}]. \tag{4}$$

Fig. 6 shows the geometry of a thick barrier and an imaginary thin screen. S and P are the sound source and the receiving point, respectively. SO is parallel to $S'Y$ and SS' is parallel to XY. $_n[Att]_0$ is the attenuation of sound by the imaginary thin screen on the path from S' to P passing Y.

After theoretical research, though the computation results of the exact solution show the resonance effect related to the thickness, *b*, with reasonable approximation, the effect of thickness for a noise having a considerable band-width is obtained from

$$_{n}[ET]_{b} = K\cdot\log(kb) \quad [\text{dB}], \tag{5}$$

where K is the value given by the single chart in Fig. 7, and

$$k = \frac{2\pi}{\lambda}. \tag{6}$$

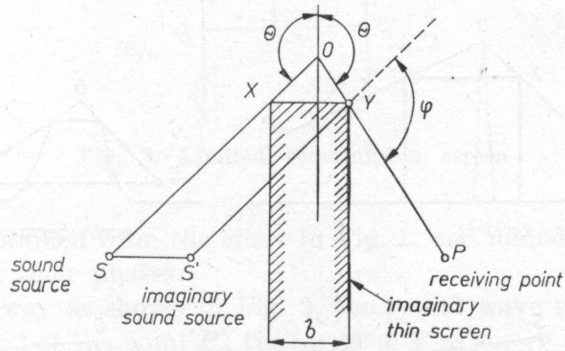

Fig. 6. Geometry of a thick barrier and an imaginary thin screen

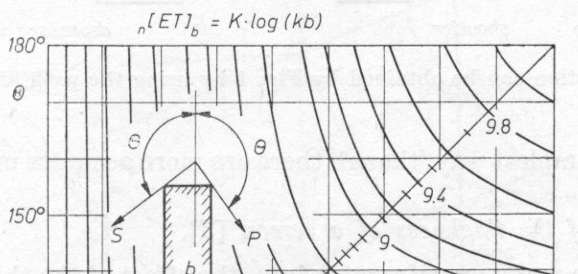

Fig. 7. The values of K in Eqn. (5) to calculate the effect of thickness of a noise barrier

(*B*) *Effect of the angle of a wedge* [6].

Many barriers of various bodies, have wedges at their corners, which cause sound diffractions. The theory of the diffraction by a wedge has been treated by many authors. Now, from the practical point of view, the effect of the wedge-angle Ω, which must be added to the attenuation by an imaginary thin screen, in a way similar to that of a thick barrier, is derived from the exact theory, as follows

$$[Att]_\Omega = [Att]_0 + [EW]_\Omega \quad [\text{dB}], \tag{7}$$

where $[Att]_\Omega$ is the noise attenuation by the wege which has wedge-angle Ω, and $[Att]_0$ is the noise reduction (obtained from the chart in Fig. 1) caused by the imaginary thin screen, as shown in Fig. 8. From many results of numerical calculations of the exact solution, we obtained a single chart of $[EW]_\Omega$ as shown in Fig. 9 with some approximations. $[EW]_\Omega$ is a function not only of the wedge-angle and the source angle θ but also the diffraction angle φ; with the notations

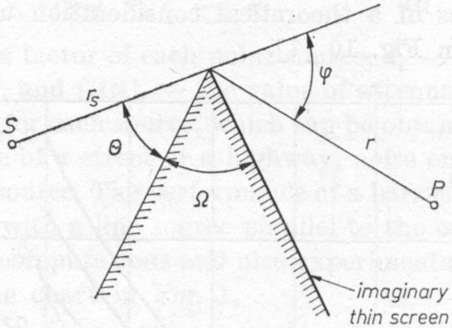

Fig. 8. Notations of the wedge diffraction

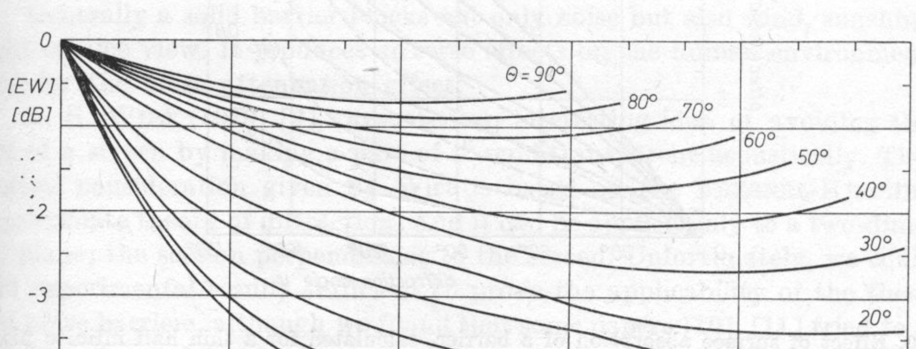

Fig. 9. Effect of wedge-angle Ω with a parameter of source angle θ

as shown in Fig. 8. But the effect of φ can be neglected, and the values of the curves show the negative largest values, in order to be on the safe side for the practical noise control. It is clear that $[EW]_\Omega$ decreases the barrier-attenuation from that of the thin screen, but not over -6 dB, and vanishes when $\Omega \to 0$.

Both methods of obtaining the effects of thickness and wedge angle are certified for their usefulness by many experiments.

6. Effect of surface absorption of the barrier

All barriers discussed above are assumed to have a rigid surface. But, the barriers treated by sound absorbing materials are widely used. The effect of surface absorption of a half infinite screen is given by using the exact theory of diffraction. The results of a theoretical consideration under some simplified condition are shown in Fig. 10 [7].

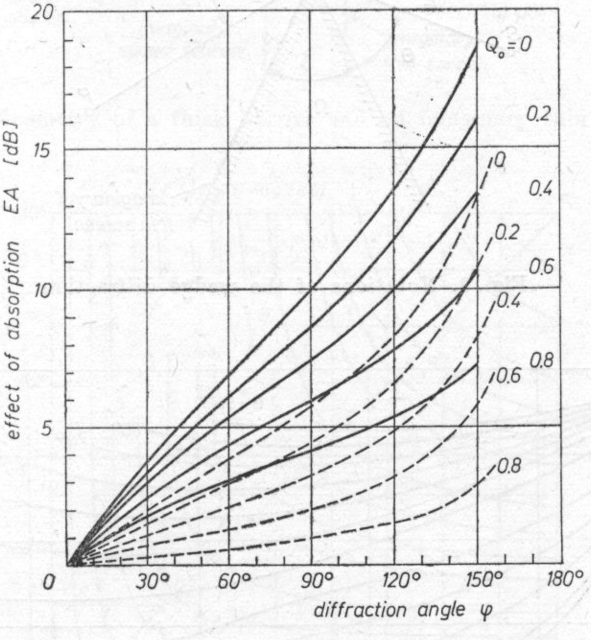

Fig. 10. Effect of surface absorption of a barrier, calculated for a thin half infinite plane. Dotted curve; for a point source, solid curve; for a line source. Q_0 — sound pressure reflection coefficient

The effect of surface absorption is a function of the diffraction angle φ, and the values are calculated in the far field for various reflection coefficients of the screen surface.

We can estimate the effect quickly by only adding the value of Fig. 10 to the value of attenuation by the reflective barrier.

7. Large extended noise source

It is a more difficult problem to obtain a theoretical solution of sound diffraction 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 the 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 added together at the receiving point.

So that the shielding effect of the barrier for a group of sources can be expressed as follows [8]

$$[Att] = 10\log\left\{\sum_{i=1}^{n}\frac{K_i}{d_i^2}\Big/\sum_{i=1}^{n}\frac{K_i}{d_i^2}\log^{-1}\frac{-[Att]_i}{10}\right\} \quad [\mathrm{dB}], \tag{8}$$

where K_i – the power factor of each point source, d_i – the distance from each source to the receiver, and $[Att]_i$ – the value of attenuation due to the barrier at the receiving point for each source, which can be obtained as described above.

For a special case of a street or a highway, noise emission 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 theoretical computations and also experimental studies are shown by a dashed-curve in the chart in Fig. 1.

8. Study of a design method of semi-transparent noise barriers

Generally a solid barrier blocks not only noise but also wind, sunshine and sight or nice view. It produces adverse effects on the human environment, except for the noise attenuation effect.

L. S. WIRT (1979) [9], presented an interesting idea of avoiding this defect of a screen by making a part of it semi-transparent acoustically. The theoretical consideration given by Wirt is based on the FRESNEL-KIRCHHOFF'S approximate theory of diffraction. And it can be applied only to a two-dimensional plane; the section perpendicular to the screen. Unfortunately, we could not find experimental results sufficient to prove the applicability of the theory to real noise barriers, although we found that some papers [10], [11] tried to apply this idea to model experiments.

The authors presented data obtained from model experiments [12]. Now, the results of further research presented here.

A) Experimental studies with a scale model

Two test screens were made from 3 mm thick aluminum plates. One has a straight line knife edge and the other has indentations in a saw-teeth shape, as shown in Fig. 11. The screen was set in an anechoic room to fill up the width of it.

A point source was located at a 0.3 m distance from the screen and was emitting $^{1/3}$ Oct. band noises. The sound pressure level distributions in the steady

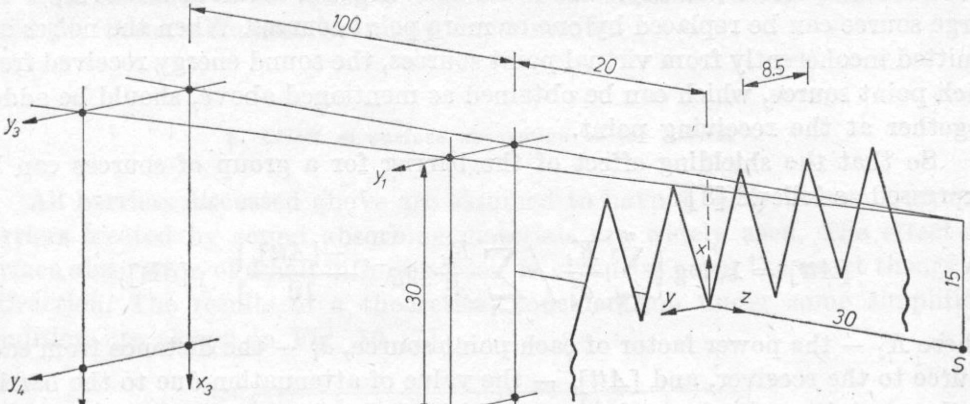

Fig. 11. Geometry of a semi-transparent screen, a point source S and measuring lines

state were measured by a 1/2 condencer-microphone moving on eight lines, $x_1 - x_4$ and $y_1 - y_4$, in the shadow zone of the screen as shown in Fig. 11. The results of the experiments are compared with the theoretical values in Fig. 13.

B) Theoretical calculations

The Helmholtz–Kirchhoff integral theorem gives the integral formula for the sound field of a point source with the approximate boundary condition, that

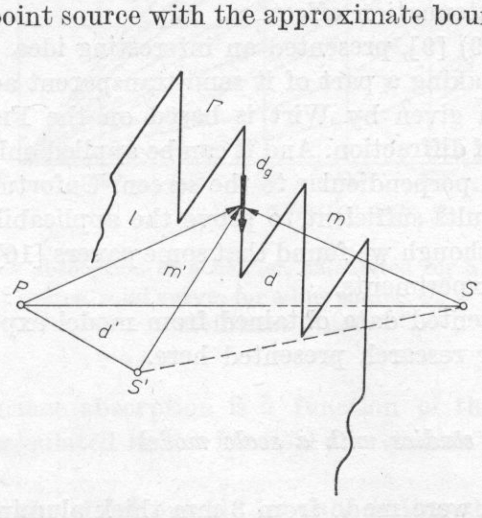

Fig. 12. Geometry and notation for Eqn. (9)

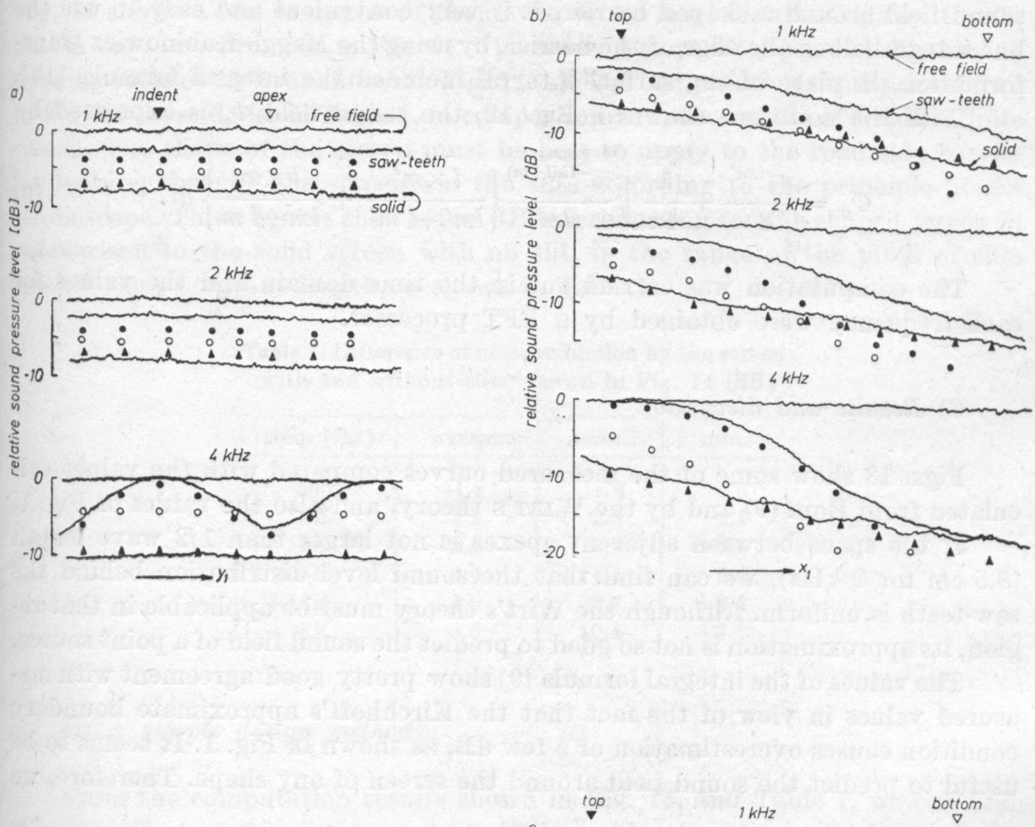

Fig 13. Experimental results, ~~ — measured, and calculated values, ● — by the line-integral Eqn. (9), ○ — by WIRT's theory, ▲ — by the chart Fig. 1

is the velocity potential on the back surface of the screen is zero [13]. For the sound field around a shaped barrier, it is very convenient and easy to use the line integral along the edge of the barrier, by using the Maggi–Rubinowicz transformation, in place of the surface-integral included the integral formula [14].

With the notations shown in Fig. 12, the sound field Φ_p is expressed by

$$\Phi_p = \frac{e^{-ikd'}}{d'} + \frac{1}{4\pi}\int \frac{e^{-ik(l+m)}}{lm}\left\{\frac{l\times m'}{lm'+l\,m'} + \frac{l\times m}{lm+l\,m}\right\} dt. \tag{9}$$

The computation was carried out in the time domain and the values for each frequency were obtained by a FFT processor.

C) *Results and discussion*

Figs. 13 show some of the measured curves compared with the values calculated from Eqn. (9) and by the WIRT's theory, and also the values of Fig. 1.

If the space between adjacent apexes is not larger than 1/2 wave length (8.5 cm for 2 kHz), we can find that the sound level distribution behind the saw-teeth is uniform. Although the Wirt's theory must be applicable in that region, its approximation is not so good to predict the sound field of a point source.

The values of the integral formula (9) show pretty good agreement with measured values in view of the fact that the Kirchhoff's approximate boundary condition causes overestimation of a few dB, as shown in Fig. 1. It seems to be useful to predict the sound field around the screen of any shape. Therefore, we

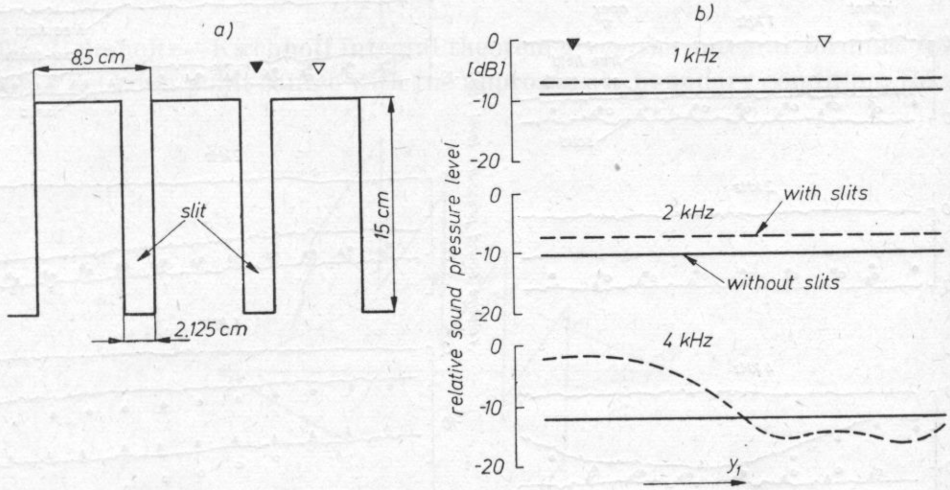

Fig. 14. Semi-transparent screen having 25 % opening ratio, (a) shape of the screen (b) sound level distribution on the y_l line in Fig. 11, calculated by the line integral Eqn. (9) — shaped screen, — solid half-infinite screen, refer to the value in free field

have computed the sound field in the shadow zone of several shaped screens. Fig. 14 shows a few examples of them, the sound level distributions on the Y_1 line in the same situation in Fig. 11. The screen has vertical parallel slits having opening ratio of 25 %, as shown in Fig. 14 (a). The computation results are shown in Fig. 14 (b) and also in Table 1, in comparison with the results of a half-infinite screen. The shape of the screen must be best to apply to the road-side barrier for looking through the screen via the slits according to the principle of the stroboscope. These curves show a few dB less reduction for the shaped screen in comparison to the solid screen with no slit, in the range of the pitch of slits smaller than 1/2 wave length, as shown in Table 1.

Table 1. Difference of noise reduction by the screen with and without slits, shown in Fig. 14 [dB]

freq. [Hz]	average	max.	min.
500	1.8	1.8	1.8
1K	2.2	2.3	2.1
2K	2.9	3.2	2.6
2.5K	3.4	4.4	2.2
3.15K	4.0	5.7	2.6
4K	3.5	10.4	−3.1

D) A simple design method

From the computation results shown in Fig. 14, and Table 1, we can find that the effect of the slits is up to 3 dB less reduction than solid half-infinite screen. The noise reduction of the solid half-infinite screen can be simply obtained by the chart in Fig. 1. Therefore, we can easily estimate the noise reduction by a semi-transparent screen with parallel slits, having 25 % opening ratio, by subtracting the average values of Table 1, provided that the pitch of slits is smaller than 1/2 wave length.

9. Conclusion

From the practical point of view, several simple methods of estimating noise reduction by various by shaped barriers are reviewed. These simple methods do not need the usage of an computer, but of course, they can be easily applied to a computer program [15].

The new application method of the simple chart to design a semi-transparent barrier is proposed. It has been clear that the line-integral formula is useful to predict the noise reduction and to obtain the correction terms for the simple chart to design the variously shaped barriers.

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