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PROPERTIES OF ACOUSTIC BARRIERS IN A FIELD OF REFLECTED WAVES

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This paper deals with the effect of selected factors on the properties of acoustic barriers.

Most attention has been paid to the influence of reflected waves which diminish the effectiveness of a barrier for the area behind it.

The considerations were limited to interiors with an extended ceiling and for cases involving one or a few noise sources. Such conditions occur often in industrial halls and in urban areas. Under these circumstances the condition of equal energy density distribution is not fulfilled, so the reverberation theory is not valid. Hence, the mirror method was used which constitutes an extension of the image source method by the mirror representation of all diffracting and absorbing surfaces.

Analytical relations were obtained, which permit the calculation of the effect of the reflected waves in decreasing the insertion loss of a barrier. Two established criteria, spatial and energetic were used. The theoretical analysis was confirmed by experimental results.

1. Introduction

The effectiveness of acoustic barriers depends on many factors which may be divided into three basic groups:

– the geometry of the system: sound source–barrier–observer,

– the properties of barrier (insulating properties, geometric diamensions, shape),

– the surrounding acoustical conditions (free field, reflected wave field, reverberant field).

The factors mentioned above are mutually interrelated. Hence a full analysis of barrier performance requires examination of the problem as a multi-parameter one.

Up to now, most attention has been paid to the problem of the geometry of the system comprising the source, barrier and observer. The influence of the surrounding acoustical conditions was not deeply investigated although it has a fundamental influence on the sound intensity level in the area behind the barrier.

The main aim of this paper is to examine the influence of the surrounding acoustical conditions in the case where the system source–barrier–observer is situated in the reflected wave field.

2. The effectiveness of a barrier

The effectiveness of a barrier is represented by the insertion loss IL' defined as the difference of the mean squared sound pressure levels at a certain point of an acoustic field, in the absence of a barrier and after its installation.

Denoting the sound pressure levels L and the average values of the squared pressures $\overline{p}^2$ by means of the subscript w in the absence of the barrier and by the subscript b with the barrier, we obtain from the definition the basic expression for the effectiveness of a barrier, given by the insertion loss

$$IL = L_w - L_b = 10 \log \frac{\overline{p}_w^2}{\overline{p}_b^2}. \tag{1}$$

In the simplest case, $\overline{p}_w^2$ represents the direct wave and $\overline{p}_b^2$ the wave diffracted at the barrier edge.

In the general case, a wave generated by a source S may reach the observer in different ways which we denote by the following subscripts for the symbols $\overline{p}^2$ and IL:

d – for the path of a wave diffracted at the upper of the barrier edge,
e – for the path of a wave diffracted at the side edges of the barrier,
i – for the wave propagated through the barrier,
r – for the waves reflected from the boundaries of the room,
o – for a direct wave without the barrier.

Thus we may write, for waves reaching an observer behind a barrier:
– without barrier

$$\overline{p}_w^2 = \overline{p}_0^2 + \overline{p}_r^2, \tag{2}$$

– with barrier

$$\overline{p}_0^2 = \overline{p}_d^2 + \overline{p}_e^2 + \overline{p}_i^2 + \overline{p}_{rb}^2, \tag{3}$$

where the subscript rb refers to waves reflected with the barrier installed. Accounting for all paths of acoustic wave transmission simultaneously, expression (1) for the barrier effectiveness can be determined by the relationship

$$IL_{deir} = 10 \log \frac{\overline{p}_0^2 + \overline{p}_r^2}{\overline{p}_d^2 + \overline{p}_e^2 + \overline{p}_i^2 + \overline{p}_{rb}^2}. \tag{4}$$

3. Barrier action in a free field

Accurate analysis of the acoustic barrier action requires a quite complex mathematical description of the acoustic wave diffraction phenomenon. However, the studies of MAEKAWA [5, 6], RATHE [10] and others have created a simplified theory leading to practically useful simple formulae for the effectiveness of the barrier in a free field. These formulae differ slightly depending on the assumptions of the restrictions but they can be written in the general form

$$IL_d = 10\log(C+qN), \tag{5}$$

where, according to Maekawa [5, 7] $C = 3$ and $q = 20$, and according to Rathe $C = 0$ and $q = 20$, assuming $N > 1$. Wells [13] derived a formula in which $C = 1$ and $q = 10$ for $N > 0$.

Differences in the value of C are significant only for small values of N. The difference in the values of q alter the value of IL by 3 dB.

In order to simplify calculations, the following formulae will be used:

$$IL_d = 10\log M, \tag{6}$$

$$M = \begin{cases} 20N & \text{for } N \geqslant 1, \\ 20N+3 & \text{for } 0 > N > 1. \end{cases} \tag{6a}$$

In these formulae N is the Fresnel number,

$$N = 2\delta/\lambda, \tag{7}$$

where λ is the wavelength and δ, according to the notation in Fig. 1a, represents the difference between the path lengths of the diffracted and the direct waves:

$$\delta = R_1+R_2-(r_1+r_2)$$
$$= h_{ef}\left[\left(\frac{1}{\sin\varphi_1}+\frac{1}{\sin\varphi_2}\right)-\left(\frac{1}{\tan\varphi_1}+\frac{1}{\tan\varphi_2}\right)\right], \tag{8}$$

where h_{ef} is the effective barrier height obtained by plotting a line from the upper barrier edge perpendicularly to the line connecting the point S of source with the point O of the observer.

In free field conditions the effectiveness of the barrier depends on two factors:

a. the geometry of the system source–barrier–observer,

b. the properties of the barrier itself.

a. *The geometry of the system source–barrier–observer*. Fig. 1 shows that in the general case of an asymmetric configuration (Fig. 1a) the estimation of the distances R_1, R_2, r_1, r_2 or h_{ef}, φ_1 and φ_2, based on the geometric positions of the source, the observer and the barrier, leads to tedious calculations. Much simpler is the symmetrical system (Fig. 1b), in which $R_1 = R_2 = R$, $r_1 = r_2 = r$, $\varphi_1 = \varphi_2 = \psi/2 = \varphi$ where ψ is the angle of diffraction.

Assuming, after Rathe, that $C = 0$ and $q = 20$ we can write the expression for the effectiveness of the barrier,

$$IL_d = 10\log\frac{\overline{p}_0^2}{\overline{p}_d^2} = 10\log 20N = 10\log\frac{80(R-r)}{\lambda} = 10\log\frac{160h}{\lambda}f(\psi), \tag{9}$$

where $f(\psi)$ is a function of the diffraction angle given by the relation

$$f(\psi) = \frac{\sin^2(\psi/4)}{\sin(\psi/2)} = \frac{1}{2}\tan\frac{\psi}{4} = \frac{1}{2}\tan\frac{\varphi}{2}. \tag{10}$$

Formula (9) does not take into account the effect of spherical wave propagation which can be expressed by the coefficient k:

$$k = \left(\frac{R}{r}\right)^2 = \frac{1}{\cos^2(\psi/2)}. \tag{11}$$

This coefficient has an obvious meaning for short distances between the sound source and the observer, a situation that occurs very often in industrial

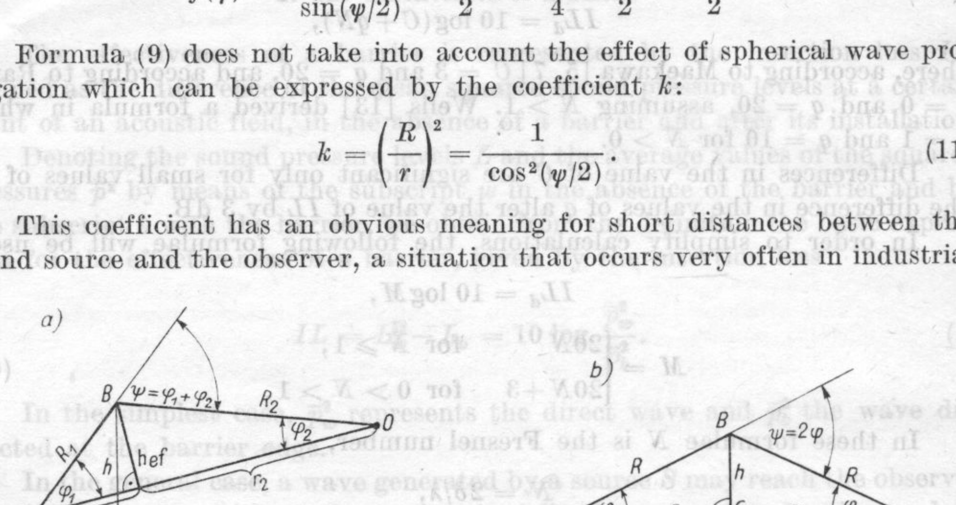

Fig. 1. The system source–barrier–observer
a) asymmetrical, b) symmetrical

conditions. It may be neglected for large distances, e.g. in the consideration of urban areas.

However, the relationship for the coefficient k represents an approximation, since the wave can be treated as a spherical one in the source–barrier region only. From the barrier to the observer it is more accurate to assume cylindrical waves.

In view of equation (11), the expression for IL_d becomes

$$IL_d = 10\log\frac{160hf(\psi)k}{\lambda} = 10\log\frac{80h}{\lambda}\frac{\tan(\psi/4)}{\cos^2(\psi/2)}, \tag{12}$$

which implies the formula

$$20N = \frac{\overline{p}_0^2}{\overline{p}_d^2} = \frac{20\cdot 4(R-r)}{\lambda}\left(\frac{R}{r}\right)^2$$

$$= \frac{1}{\lambda}\frac{20\cdot 8h}{\sin(\psi/2)}\frac{\sin^2(\psi/4)}{\cos^2(\psi/2)} = \frac{20\cdot 4h}{\lambda}\frac{\tan(\psi/4)}{\cos^2(\psi/2)}. \tag{13}$$

Fig. 2 shows IL_d as a function of the diffraction angle for $h/\lambda = 1$ and $h/\lambda = 10$. Curves *a* have been calculated with the formula usually found in the references [7, 10], where this formula is without the coefficient k. Curves *b* were calculated according to (12).

In order to compare the analytical results, the additional curves *c* were plotted in Fig. 2 for identical ratios of h_{ef}/λ, obtained from the diagram of MAEKAWA [7] using the diffraction angle as an independent variable. Similar curves are also obtained by an identical treatment of the curves of KURZE [4].

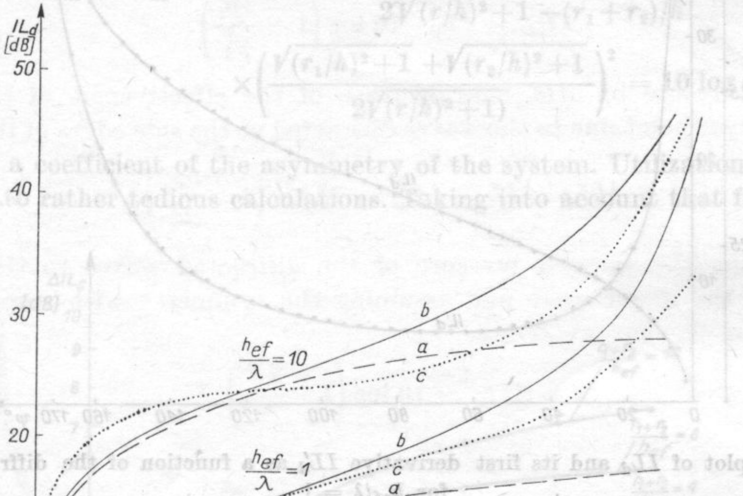

Fig. 2. Relationship between IL_d and the diffraction angle ψ for symmetrical system for $h_{ef}/\lambda = 1$ and $h_{ef}/\lambda = 10$

a) curve calculated from formula (10) without correction for the sphericity of the waves, *b*) curve calculated from formula (12) taking into account a correction for the sphericity of the waves, *c*) curve obtained by replotting of the graph of MAEKAWA [7]

The curves *b* and *c* show an increase compared to curve *a* of the IL_d for high values of the diffraction angle ψ, if the correction for sphericity of waves has a greater significance. It confirms the usefulnes of introducing this correction, although differences between curves *b* and *c* indicate that further analysis is required.

In order to analyse more precisely the changes of IL_d versus diffraction angle the first derivative of IL_d has been calculated and plotted in Fig. 3,

$$IL_d' = \frac{d(IL_d)}{d\psi}. \tag{14}$$

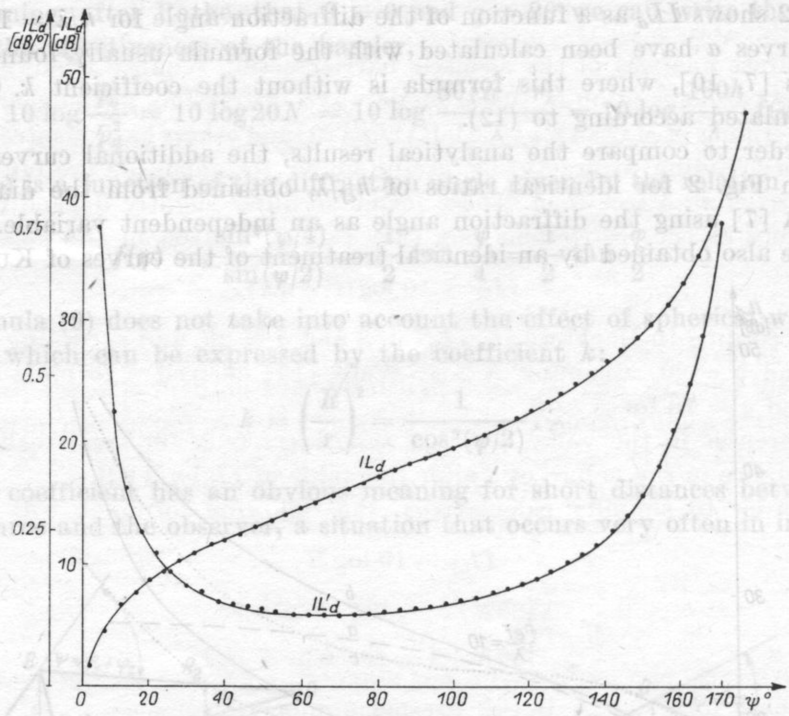

Fig. 3. The plot of IL_d and its first derivative IL'_d as a function of the diffraction angle for $h_{ef}/\lambda = 1$

The curve IL'_d as a function of the diffraction angle ψ shows the sensitivity of the source–barrier–observer system to changes in the angle. For a fixed height of barrier it resolves itself into a sensitivity to changes in the distance between the source or the observer and the barrier. The curve $IL_d = f(\psi)$ implies that within a range of diffraction angles $30° < \psi < 120°$ the value of IL'_d is small and remains within the limits 0.12 - 0.15 dB/°. Within this range of angles, the system shows little sensitivity to changes in the diffraction angle.

This permits the introduction of a ,,criterion of 30°" which, taking into account the economical arguments, determines the optimal value of the diffraction angle for large distances between the sound source and the observer compared with the effective height of the barrier. This criterion leads to a practical conclusion which can be applied in town planning acoustics.

For small distances between the source and the observer to the barrier a criterion of 120° can be introduced. In situation where the diffraction angle ψ is about 120° it is useful to make this angle as large as possible, because it very greatly increases the effectiveness of the barrier. This conclusion may be highly important in the design of industrial interiors and offices.

From these considerations an additional problem arises in the asymmetry of the arrangement. Relatively small errors should be expected when an asymmetrical arrangement (Fig. 1a), which is inconvenient for analytical purposes, is transformed into a more convenient symmetrical one (fig. 1b) within a range of 30°-120° for the diffraction angle.

The difference ΔIL_s between IL_{dns} for an asymmetric arrangement and IL_{ds} for a symmetric one, assuming that the distance between the source and the observer is fixed, i.e. $r_1+r_2 = 2r$ = const, may be calculated from the relation

$$\Delta IL_s = IL_{dns} - IL_{ds} = 10\log \frac{\sqrt{(r_1/h)^2+1}+\sqrt{(r_2/h)^2+1}-(r_1+r_2)/h}{2\sqrt{(r/h)^2+1}-(r_1+r_2)/h}\times \times\left(\frac{\sqrt{(r_1/h)^2+1}+\sqrt{(r_2/h)^2+1}}{2\sqrt{(r/h)^2+1)}}\right)^2 = 10\log\varepsilon, \quad (15)$$

where ε is a coefficient of the asymmetry of the system. Utilization of formula (15) leads to rather tedious calculations. Taking into account that for practical

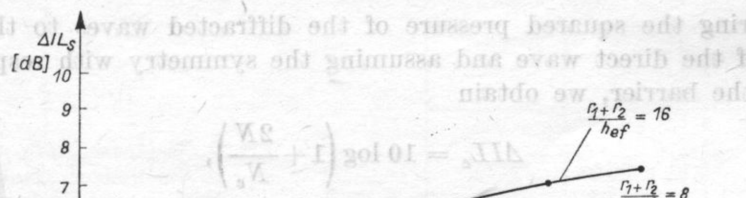

Fig. 4. Corrections ΔIL_s resulting from transformation of an asymmetrical arrangement to a symmetrical one as a function of the asymmetry r_2/r_1 or r_1/r_2

purposes the relation $\Delta IL_s = f(r_2/r_1)$ or $\Delta IL_s = f(r_1/r_2)$ is more convenient, it has been calculated for several values of parameter $(r_1+r_2)/h_{ef}$ and presented in Fig. 4. From these relations it results that, as expected, even for high values of r_1/r_2 or r_2/r_1 the error caused by the transformation from an asymmetric arrangement into a symmetric one is not high and can be included as the correction according to Fig. 4.

b. *Parameters of the barrier*. The width of the barrier and its insulating properties for airborne sounds will be examined as the parameters of the barrier which may cause a reduction in its resultant effectiveness.

In order to consider the influence of the barrier width on IL_d let us denote by $\overline{p}_e^2$ the mean squared sound pressure of the wave arriving at the observer in consequence of diffraction at the edge of one side of the barrier. Since the waves are diffracted at two side edges of a barrier, we can write

$$IL_{de} = 10\log\frac{\overline{p}_0^2}{\overline{p}_d^2+2\overline{p}_e^2} = 10\log\frac{\overline{p}_0^2/\overline{p}_d^2}{1+2\overline{p}_e^2/\overline{p}_d^2}. \tag{16}$$

With expression (9) we get

$$IL_{de} = IL_d - 10\log\left(1+\frac{2\overline{p}_e^2}{\overline{p}_d^2}\right). \tag{17}$$

Let us denote by ΔIL_e the decrease of the effectiveness of the barrier at the observer point due to the waves diffracted at the side edges of the barrier:

$$\Delta IL_e = IL_d - IL_{de} = 10\log\left(1+\frac{2\overline{p}_e^2}{\overline{p}_d^2}\right). \tag{18}$$

Referring the squared pressure of the diffracted waves to the squared pressure of the direct wave and assuming the symmetry with respect to the width of the barrier, we obtain

$$\Delta IL_e = 10\log\left(1+\frac{2N}{N_e}\right), \tag{19}$$

where

$$20N = \frac{\overline{p}_0^2}{\overline{p}_d^2}, \quad 20N_e = \frac{\overline{p}_0^2}{\overline{p}_e^2}. \tag{20}$$

Using the notation from Fig. 5 and relation (13), we may write

$$\Delta IL_e = 10\log\left[1+\frac{2(R-r)}{W-r}\frac{R^2}{W^2}\right] \tag{21}$$

and after further transformation

$$\Delta IL_e = 10\log\left\{1+\frac{2\left(\sqrt{r^2+h_{ef}^2}-r\right)(r^2+h_{ef}^2)}{\left[\sqrt{r^2+(B/2)^2}-r\right][r^2+(B/2)^2]}\right\}. \tag{22}$$

The relationship of ΔIL_e as a function of the ratio of the barrier width B to its effective height h_{ef}, with r/h_{ef} as a parameter, is shown in Fig. 6. This relationship enables to choose the width of the barrier, when a given decrease in its effectiveness is admitted.

In a similar way we can consider the decrease of barrier effectiveness due to the limited insulating properties of the barrier expressed by the insertion loss IL_i,

$$IL_i = 10\log\frac{\overline{p}_0^2}{\overline{p}_i^2} = 10\log\frac{1}{\tau}, \tag{23}$$

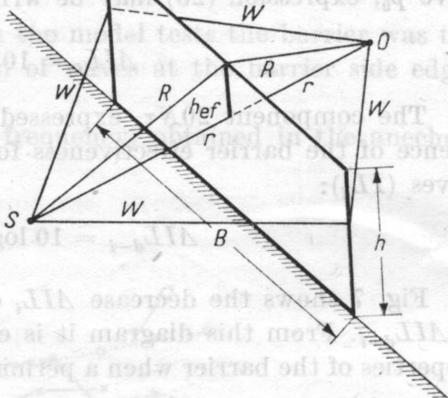

Fig. 5. The system source–barrier–observer in case of a limited barrier width B

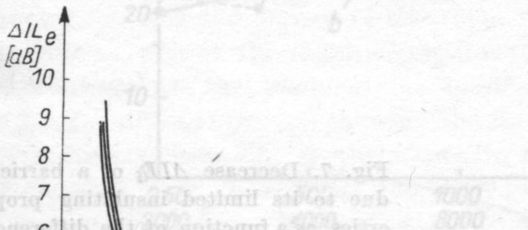

Fig. 6. Decrease ΔIL_e of a barrier, due to sound transmission along its side edges, as a function of the ratio of the barrier width B to its effective height h_{ef}

where $\overline{p}_i^2$ is the mean squared sound pressure of a wave penetrating the barrier, and τ is the transmission coefficient of the barrier.

The effectiveness of a barrier in the case of the joint action of diffracted waves and waves penetrating the barrier is then

$$IL_{di} = 10\log\frac{\overline{p}_0^2}{\overline{p}_d^2+\overline{p}_i^2} = 10\log\frac{\overline{p}_0^2/\overline{p}_d^2}{1+\overline{p}_i^2/\overline{p}_d^2} = IL_d - 10\log\left(1+\frac{\overline{p}_i^2}{\overline{p}_d^2}\right). \qquad (24)$$

Hence, for the decrease ΔIL_i, caused by the part of the energy which penetrates through the barrier, we get

$$\Delta IL_i = IL_d - IL_{di} = 10\log\left(1+\frac{\overline{p}_i^2}{\overline{p}_d^2}\right). \qquad (25)$$

After referring $\overline{p}_i^2$ and $\overline{p}_d^2$ to the mean squared sound pressure of the incident wave $\overline{p}_0^2$, expression (25) may be written in the form

$$\Delta IL_i = 10\log(1+20N\tau). \tag{26}$$

The component $20N\tau$, expressed in logarithmic scale, represents the difference of the barrier effectiveness for penetrating waves (IL_i) and diffracted waves (IL_d):

$$\Delta IL_{d-i} = 10\log 20N\tau = IL_d - IL_i. \tag{27}$$

Fig. 7 shows the decrease ΔIL_i of the barrier effectiveness as a function of ΔIL_{d-i}. From this diagram it is easy to determine the required insulating properties of the barrier when a permissible decrease of effectiveness is assumed.

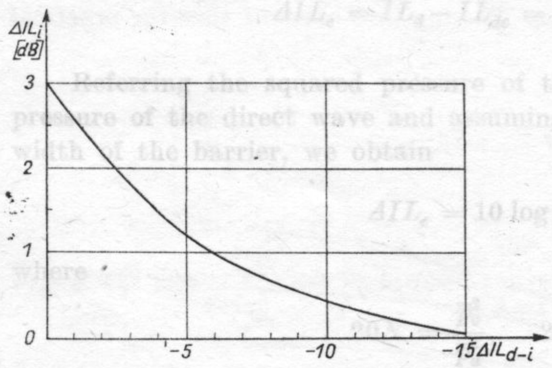

Fig. 7. Decrease ΔIL_i of a barrier, due to its limited insulating properties, as a function of the difference of effectiveness ΔIL_{d-i} between a wave penetrating the barrier and the diffracted wave

3. Experimental results for free field conditions

Experiments in free field conditions were carried out in an anechoic chamber over a frequency range of 250 Hz - 2000 Hz, and in an anechoic model with dimensions 83×110×150 cm in a scale of 1 : 8, i.e. for a frequency range 2000 Hz - 16000 Hz.

The aim of the investigations was to check the agreement of the experimental results with the analytical ones and to assess the usefulness of model tests for further experiments involving a field of reflected waves.

The sound sources used were: loudspeaker of 14 cm diameter for tests in the anechoic chamber and 8.3 cm for the model tests. The irregularity of the directional characteristics of the loudspeakers was ±3 dB in the frequency ranges of the experiments. A 1/2" microphone was used in the anechoic chamber and 1/8" microphone for model experiments.

Third octave band noise was used as a signal. The barrier used was partially reflecting, with transmission properties such that the energy penetrating the barrier was at least 10 dB below that diffracted at the edge of the barrier, i.e. $IL_i - IL_d > 10$ dB.

Both in the anechoic chamber and in the model tests the barrier was the width of the room so that the diffraction of waves at the barrier side edges could be neglected.

Experimental results for IL_d versus frequency, obtained in the anechoic

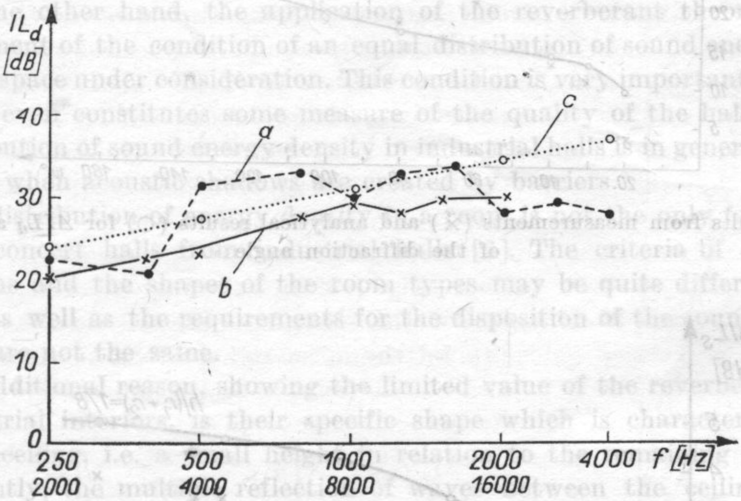

Fig. 8. Experimental results for ΔIL_d versus frequency, obtained in an anechoic chamber (curve *a*) and on a model (curve *b*)

chamber and in the model, are shown in Fig. 8. These results were obtained for a symmetrical arrangement with the following parameters (notation according to Fig. 1b):

$$h_{ef} = 20 \text{ cm}, \quad \psi = 60°.$$

The obtained results show good agreement and have confirmed the validity of the model for further investigations.

The results for IL versus the diffraction angle, obtained in the anechoic chamber for $h_{ef}/\lambda = 1.18$, are shown in Fig. 9.

The results are in conformity with the analytical curve and confirm the necessity of introducing a coefficient k for the sphericity of the waves at high values of the diffraction angle.

Results for the correction ΔIL_s, arising from an asymmetric arrangement with $h/(r_1+r_2) = \frac{1}{8}$ as the parameter, are given in Fig. 10.

According to the analytical results, the values of the corrections ΔIL_s, for the parameter values mentioned above, do not exceed 4.5 dB.

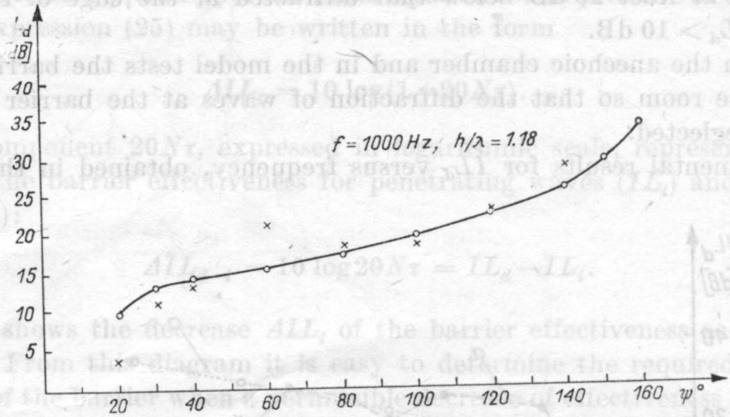

Fig. 9. Results from measurements (×) and analytical results (○) for ΔIL_d as a function of the diffraction angle

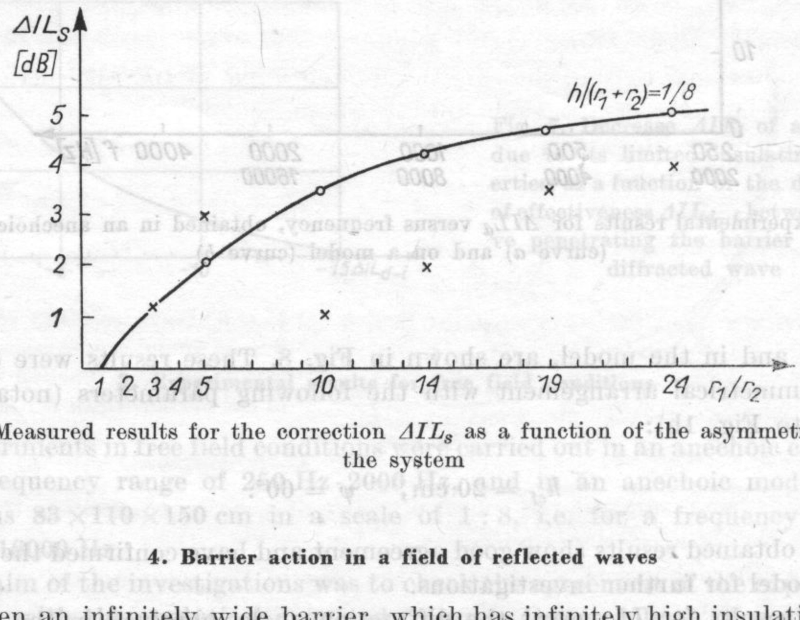

Fig. 10. Measured results for the correction ΔIL_s as a function of the asymmetry r_1/r_2 of the system

4. Barrier action in a field of reflected waves

When an infinitely wide barrier, which has infinitely high insulating properties, is placed in a field of reflected wave, then its effectiveness is given by formula (4):

$$IL_{dr} = 10 \log \frac{\overline{p}_0^2 + \overline{p}_r^2}{\overline{p}_d^2 + \overline{p}_{rb}^2} = 10 \log \frac{1 + \overline{p}_r^2/\overline{p}_0^2}{\overline{p}_d^2/\overline{p}_0^2 + \overline{p}_{rb}^2/\overline{p}_0^2}. \quad (28)$$

Formula (28) implies that if the observer is situated at the place where the energy of the reflected wave dominates the direct wave ($\overline{p}_r^2 > \overline{p}_0^2$), then the effectiveness of the barrier is very low ($IL_{dr} \cong 0$).

The influence of reflected waves in decreasing the effectiveness of barriers is usually discussed in terms of the reverberant theory of rooms. This theory leads to the conclusion that to obtain a high effectiveness of the barrier the reverberation time of the interior must be low [8]. It requires the use of the great quantity of absorbing material which is often expensive and difficult from a practical point of view. This is the reason why acoustic barriers are not very popular in practice.

On the other hand, the application of the reverberant theory demands the fulfilment of the condition of an equal distribution of sound energy density inside the space under consideration. This condition is very important for concert halls and even constitutes some measure of the quality of the hall. However, the distribution of sound energy density in industrial halls is in general irregular, especially when acoustic shadows are created by barriers.

The distribution of energy density in a room is not the only factor distinguishing concert halls from industrial halls [2]. The criteria of quality, the proportions and the shapes of the room types may be quite different or even opposite as well as the requirements for the disposition of the sound absorbing material are not the same.

An additional reason, showing the limited value of the reverberant theory for industrial interiors, is their specific shape which is characterized by an extended ceiling, i.e. a small height in relation to the remaining dimensions. Consequently, the multiple reflection of waves between the ceiling and the floor primarily decides the overall energy of the reflected waves.

Then as in urban areas a constant drop of the acoustic pressure level by 3 dB with doubling the distance takes place, without the occurrence of a critical distance [2, 12].

In consequence, the concept of a diffuse field will be replaced in the present paper by the a concept of a reflected wave field and, instead of the reverberant theory, the mirror method which constitutes an extension of the image source method will be used.

5. The mirror method

The image source method is used mainly as a qualitative means of imaging the reflected wave field by means of additional sound sources. This method has had a wide didactic application, but it can now be used as an analytical method [9] due to computer developments.

By the mirrorlike reproduction of the elements in the room (barriers, absorbing surfaces), the image source method may be extended into a method which we will call the mirror method. This method will be treated as an analytical method for calculating the sound intensity at any point of an acoustic field, taking into account the effect of the barrier and the absorbing surfaces.

For simplification, the analysis will be limited to rooms with an extended ceiling, which is, in general, very often the case in industrial halls. The problem thereby resolves itself into an analysis of the acoustic conditions in a room with two parallel reflecting surfaces and corresponds to the situation where image sources are arranged in only one axis.

Let us assume that there is in the room only one source generating a spherical wave. The image sources will also radiate spherical waves. The acoustic power of the image sources will decrease respectively, being multiplied by the coefficient of reflection β, raised to a power corresponding to the number of times the wave has been reflected.

Assuming that the source is placed on the floor (Fig. 11), the following expression is obtained for the resulting reflected wave sound intensity for the noise signal at an observation point also on the floor, at a distance r from the source:

$$I_r \cong \frac{P}{\Psi} = \left[\beta + \frac{(1+\beta)^2}{(2H)^2} \sum_{i=1}^{\infty} \frac{\beta^{2i-1}}{i}\right]; \quad (29)$$

H is the room height, P — the acoustic power of the source, and $\Psi < 2\pi$ — the solid angle for the image sources.

The effect of the reflected waves reaching the space behind the barrier can be reduced (i.e. the propagation of waves produced by the image sources) can be decreased by the following two methods:

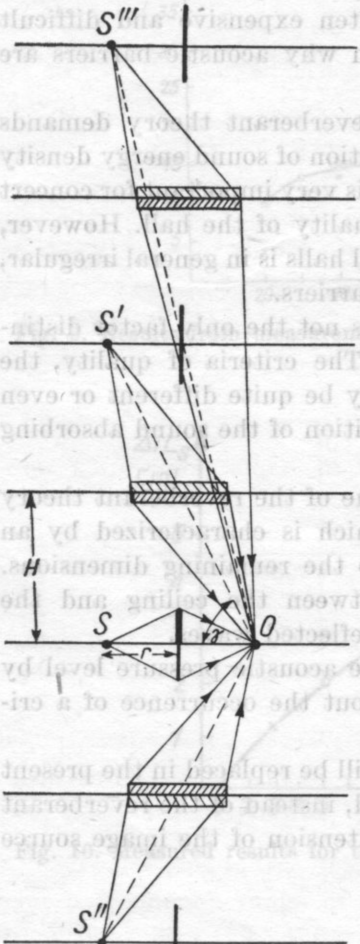

Fig. 11. The principle of the mirror method

a. the choice of the height, shape and situation of the barrier;

b. a reduction of the coefficient of reflection of the surfaces situated above the barrier by fastening into the ceiling an absorbing band of suitable width.

The proper application of both methods can be analysed graphically by extending the method of image sources and by the mirrorlike reproduction of the barrier and absorbing bands, to produce image barriers and image absorbing bands. The waves produced by the image sources will arrive at the observation point without diffraction only when there are no image elements in their paths.

An analysis of the paths of rays representing the waves propagated from the image sources (Fig. 11) suggests the idea of treating the absorbing bands as band-barriers which limit the propagation of the waves generated by the image sources. This interpretation could be used for analytical purposes and would lead to uniform method of accounting for the effect of the barriers and the absorbing bands, based on the phenomenon of diffraction.

The action of the edges of the absorbing bands corresponds with the physical phenomenon of the scattering of acoustic energy in the form of the so-called edge effect, similar to the phenomenon of diffraction at an edge. This partially justifies the idea of band–barriers although a more detailed theoretical analysis is still required.

In the present paper the development of the band-barriers method as an analytical method has two aims:

— the initial evaluation of whether the method leads to simple mathematical relationships allowing the action of the absorbing bands and the barriers to be considered jointly and

— the checking of the agreement between the experimental and the analytical results obtained from the expressions based on the band-barrier concept.

Regarding the concept of band-barriers, the absorbing bands may be treated as a set of two barriers with an effective height related to the width of the absorbing band. The length of the band corresponds to the width of the barrier and the reflection coefficient β_a of the band material corresponds to the transmission coefficient τ of the barrier.

From Fig. 12 it can be easily seen that regions near the barrier are protected most effectively by the absorbing bands and this area expands for waves produced by the higher order image sources.

However, an area far behind the barrier is best protected against reflected waves by an image barrier, since near the barrier the image barrier limits only the propagation of those waves that are generated by lower order image sources. Also, with increasing distance, the number of image sources that are screened increases.

The effects of the image barriers and absorbing bands complement each other and their joint action provides a substantial limitation of the effect of reflected waves on the barrier *IL*.

The mirror method described above leads to more economical solutions than the statistical method. For industrial halls with extended ceilings and only a few noise sources it is possible to obtain a given reduction of reflected waves in a chosen region behind the barrier using much smaller quantities of sound absorbing material.

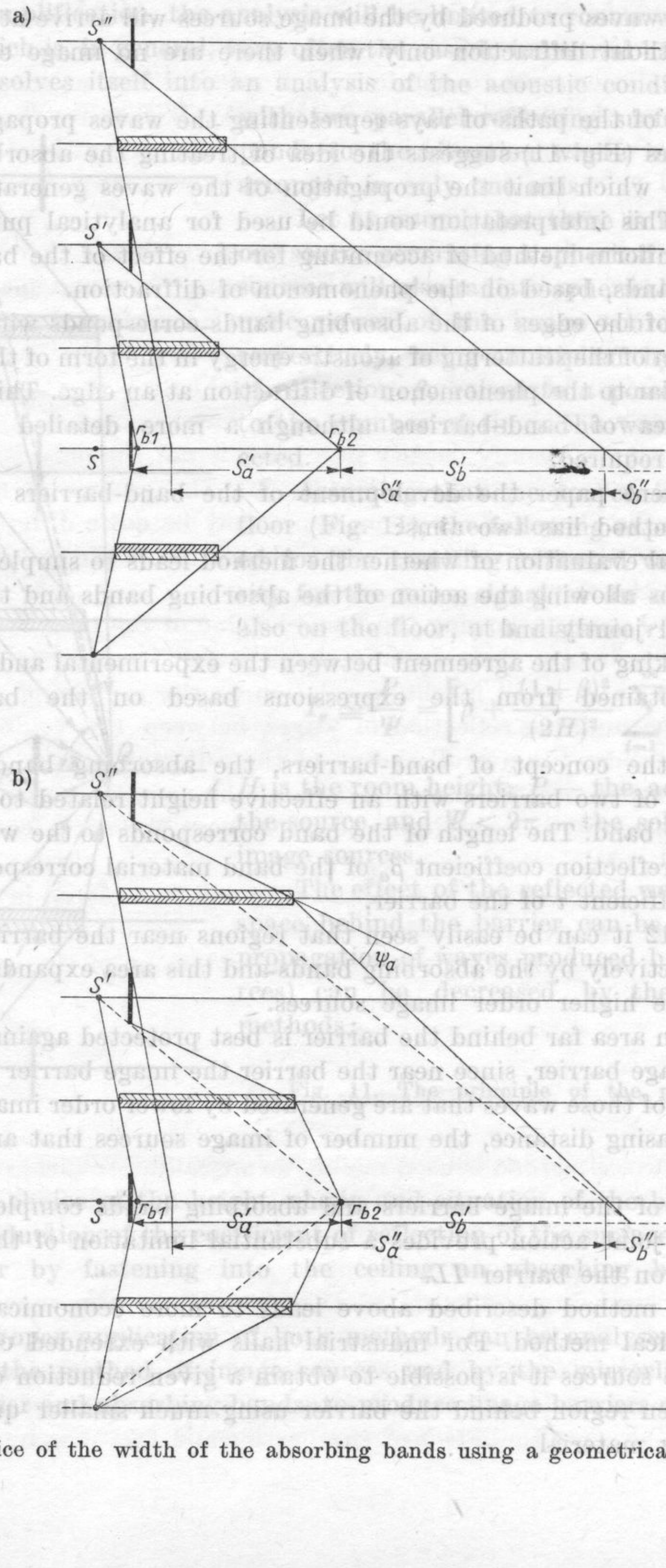

Fig. 12. Choice of the width of the absorbing bands using a geometrical method

6. Calculation of the IL_d in a field of reflected waves for the joint action of barriers and absorbing bands

In order to select the parameters of the barriers and absorbing bands giving jointly a sufficiently high (for an assumed criterion) limitation of reflected waves propagation (which reduces the effectiveness of the barriers), let us introduce the following symbols for the averaged values of the squared acoustic pressures at the observer point:

$\bar{p}_0^2$ – for the direct wave without the barrier,

$\bar{p}_d^2$ – for the wave diffracted at the barrier,

$\bar{p}_r^2$ – for the reflected waves (originating from the image sources) without the barrier and absorbing band,

$\bar{p}_{ra}^2$ – for the reflected waves limited by the action of the absorbing bands,

$\bar{p}_{rb}^2$ – for the reflected waves limited by the image barriers,

$\bar{p}_{rab}^2$ – for the reflected waves limited by the joint action of the absorbing bands and image barriers.

The effectiveness of the barriers in a field of reflected waves can be given as

$$IL_r = 10\log\frac{\bar{p}_0^2+\sum_{i=1}^{\infty}\bar{p}_{rai}^2}{\bar{p}_d^2+\sum_{i=1}^{\infty}\bar{p}_{rabi}^2}. \tag{30}$$

For simplification let us consider separately the effect of image barriers which create an acoustical shadow for distances $r > r_{b2}$ and $r < r_{b1}$ behind the barrier and the effect of absorbing bands which create a shadow for the distances $r_{b1} < r < r_{b2}$. Thus the effectiveness of a barrier with the effect of reflected waves limited by the action of the image barriers can be expressed as

$$IL_{rb} = 10\log\frac{\bar{p}_0^2+\sum_{i=1}^{\infty}\bar{p}_{ri}^2}{\bar{p}_d^2+\sum_{i=1}^{\infty}\bar{p}_{rbi}^2} = IL_d - 10\log\frac{1+\left(\sum_{i=1}^{\infty}\bar{p}_{rbi}^2\right)/\bar{p}_d^2}{1+\left(\sum_{i=1}^{\infty}p_{ri}\right)/\bar{p}_0^2} = IL_d - \Delta IL_b, \tag{31}$$

where ΔIL_b is the decrease of the barrier effectiveness, resulting from the energy of the reflected waves, for the region where the image barriers are effective. Similarly, the effectiveness of a barrier with the effect of the reflected waves limited by the action of absorbing bands becomes

$$IL_{ra} = 10\log\frac{\bar{p}_0^2+\sum_{i=1}^{\infty}\bar{p}_{rai}^2}{\bar{p}_a^2+\sum_{i=1}^{\infty}\bar{p}_{rai}^2} = IL_d - 10\log\frac{1+\left(\sum_{i=1}^{\infty}\bar{p}_{rai}^2\right)/\bar{p}_d^2}{1+\left(\sum_{i=1}^{\infty}\bar{p}_{rai}^2\right)/\bar{p}_0^2} = IL_d - \Delta IL_a, \tag{32}$$

where ΔIL_a is the decrease of the barrier effectiveness due to the presence of reflected waves in the region of the action of the absorbing bands.

In order to examine the above relationships in detail, the following simplifying assumptions will be made:

— The acoustic energy of the waves diffracted at both edges of the absorbing bands and reaching the observer is equal for both paths,

— for reflections of higher order the asymmetrical situation can be replaced by a symmetrical one, by introducing asymmetry coefficients of equation (15): ε_{bi} for the image barriers, and ε_{ai} for the absorbing bands.

In order to account for the affect of reflected waves under the above assumptions, the following coefficients will be introduced:

a coefficient for the waves generated by the i-th image source in conditions without a barrier and without absorbing bands

$$m_i = \frac{\overline{p}_{ri}^2}{\overline{p}_0^2} = \beta^i \cos^2 \gamma_i, \tag{33}$$

where β is the coefficient of reflection of the surface above the barrier before the absorbing band have been placed and γ_i is the angle at which the wave, generated by the i-th image source reaches the observer,

a coefficient representing the influence of the reflected waves at the observation point in the situation when the barrier is installed without absorbing bands

$$\eta_{bs} = \frac{\sum\limits_{i=1}^{\infty} \overline{p}_{rbi}^2}{\overline{p}_0^2} = \sum_{i=1}^{\infty} \frac{m_i}{\varepsilon_{bi}} \frac{\mu}{\mu_{bi}}, \tag{34}$$

a coefficient representing the influence of the reflected waves after the installation of the barrier and the absorbing band for observation points situated in the region where the absorbing band is effective

$$\eta_{as} = \frac{\sum\limits_{i=1}^{\infty} \overline{p}_{rai}^2}{\overline{p}_d^2} = \sum_{i=1}^{\infty} \frac{2\mu}{\mu_{ai}} \frac{m_i}{\varepsilon_{ai}}. \tag{35}$$

Numbers M are related to the Fresnel numbers by relation (6a). M_{bi} and M_{ai} characterize the influence of waves diffracted at the edges of the image barriers and at both edges of the absorbing bands, respectively, whereas M concerns the direct wave diffracted at the edge of the barrier.

Substituting relations (13), (33), and (34) in formula (31), and (13), (33) and (34) — in formula (32), we obtain the following expressions for the decrease of the effectiveness of the barrier due to the reflected waves:

for the region where the image barriers are effective

$$\Delta IL_b = 10 \log \frac{1+\eta_{bs}}{1+\sum\limits_{i=1}^{\infty} m_i} = \frac{1+\sum\limits_{i=1}^{\infty} \frac{\mu m_i}{\mu_{bi}\varepsilon_{bi}}}{1+\sum\limits_{i=1}^{\infty} m_i}, \tag{36}$$

for the region where absorbing bands are effective

$$\Delta IL_a = 10 \log \frac{1+\eta_{as}}{1+\eta_{as}/M} = 10 \log \frac{1+\sum_{i=1}^{\infty} \frac{2M}{M_{ai}} \frac{m_i}{\varepsilon_{ai}}}{1+\sum_{i=1}^{\infty} \frac{2}{M_{ai}} \frac{m_i}{\varepsilon_{ai}}}, \tag{37}$$

where $M = 20N$ for $N \geqslant 1$ and $M = 20N+3$ for $1 > N > 0$. When the regions, where the image barriers and the absorbing bands are effective, are superposed (Fig. 12b), a double diffraction of the waves generated by the image sources takes place. These conditions correspond to the problem of wave diffraction at two independent barriers which leads to more complicated analytical relationships.

Formulae (36) and (37), despite of the simplifications in their assumption, permit an estimation of the reduction of barrier effectiveness when the propagation of reflected waves is reduced or, inversely, an estimation of the limitation of reflected waves necessary to obtain a required barrier effectiveness.

From a practical point of view this leads to the determination of the width of the absorbing band for given geometrical conditions of the barrier situation and for given conditions of interior.

7. The optimum width of the absorbing band

The choice of the width of the absorbing band depends on the criteria assumed for acoustic conditions behind the barrier. Two different criteria may be used: (a) spatial, (b) energetic (local).

The *spatial criterion* consists in providing an acoustic shadow for the whole area behind the barrier.

It is evident from Fig. 12a that if, due to the joint action of an image barrier and an absorbing band, the whole area behind the barrier will be covered with an acoustic shadow from an image source of the 1st order, this area will be also covered with acoustic shadow from sources of higher orders.

In this case the analysis of the absorbing band action can be limited to the examination of the effect for the first reflection only. For a given room and for assumed barrier parameters it is then most convenient to determine the width of the absorbing band by a graphical method. For the diffraction angle of a wave generated from the image source S', $\psi_a = 0$ (Fig. 13), the rays originating from the image source S' and passing the upper edges of the real and image barriers are drawn. These rays divide the area of action of the barrier and the absorbing band against the reflected waves for any observer point.

The width of the absorbing band d_g is determined by the distance between the above rays. This width will be smallest if the band is mounted on the ceiling.

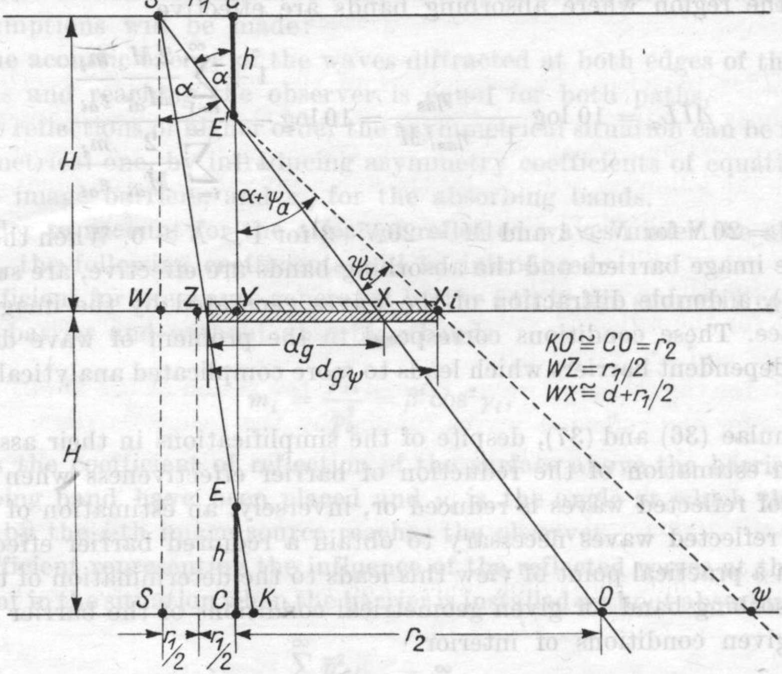

Fig. 13. Illustration of the space criterion for the case of a single reflection

Taking into account the diffraction angle $\psi_a > 0$ (broken line in Fig. 13), the width of the absorbing band should be correspondingly larger. It is evident that when the space criterion is used, the band should be placed asymmetrically above the barrier, and nearer the observer point.

In order to determine analytically the dependence of the width of the band on the system parameters, we make the following simplifications (Fig. 13): the range of action of the absorbing band

$$KO \cong r_2, \tag{38}$$

the point Z of the absorbing band edge depends only on the distance r_1 between the source and the barrier and is placed half way between them

$$ZY \cong WZ \cong r_1/2, \tag{39}$$

the point X depends on all of the system parameters, namely on the distance r_1 between the source and the barrier, on the barrier height h and on the room height H.

For the angle of diffraction at the image barrier $\psi_a < (90° - \alpha)$ (broken line in Fig. 13) we can write

$$\tan(\alpha + \psi_a) = \frac{d_{g\psi} - r_i/2}{H - h}. \tag{40}$$

Using the formula for the tangent of the sum of two angles, after transformation we obtain

$$d_g = \frac{r_1\left(H - \frac{h}{2}\right)/h + (H - h - r_1^2/2h)\tan\psi_a}{1 - r_1 \tan\psi_a/h}. \tag{41}$$

For the diffraction angle $\psi_a = 0$ as in Fig. 12a, relation (41) reduces to the following form:

$$d_g = \frac{r_1(H - h/2)}{h}. \tag{42}$$

Usually $H \gg h/2$, and an approximate but simple relation which facilitates practical calculations is obtained:

$$d_g \cong \frac{r_i H}{h}. \tag{43}$$

A comparison of Figs. 14a and 14b shows the Y-shaped barriers to be more effective than the simple ones. For the same effective height of both

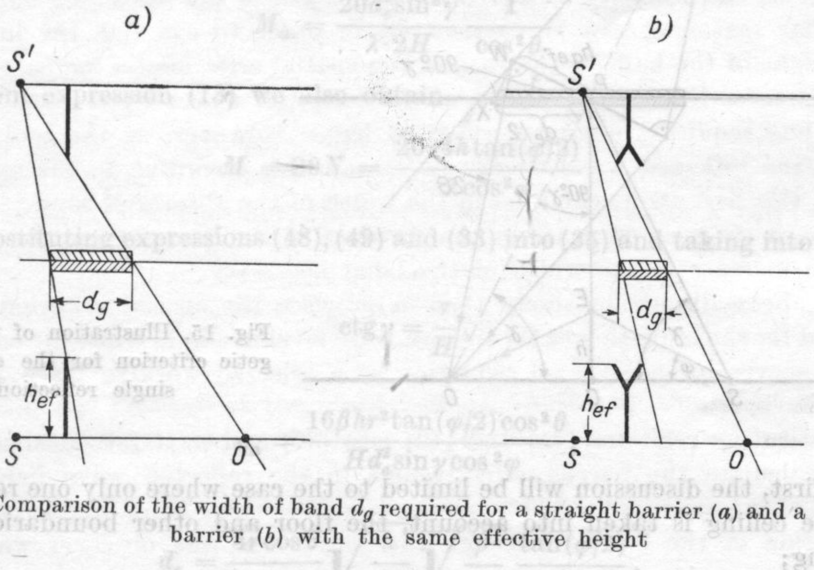

Fig. 14. Comparison of the width of band d_g required for a straight barrier (a) and a Y-shaped barrier (b) with the same effective height

kinds of barriers the same conditions of acoustic shadow behind the barrier are obtained for a smaller width of absorbing band when a Y-shaped barrier is used.

The *energetic criterion* is based on the ratio of the reflected wave energy to the energy of the diffracted waves, for a chosen observation point. This criterion resolves itself into the choice of a suitable value of the coefficient η_{as} given by formula (35).

Many features of the energetic criterion contrast with those of the spatial criterion. The spatial criterion accounts qualitatively for the joint action of the image barriers and the absorbing bands in order to cover with acoustic shadow as much of the area behind the barrier as possible. This criterion concers points of observation placed rather distantly from the barrier.

In contrast, the energetic criterion is concerned with one chosen point near the barrier and represents quantitatively the action of the absorbing band.

In order to determine the relationship between the required value of the width of the absorbing band for an assumed value of η_a and for the other parameters of the barrier and the room let us make the following simplifying assumptions:

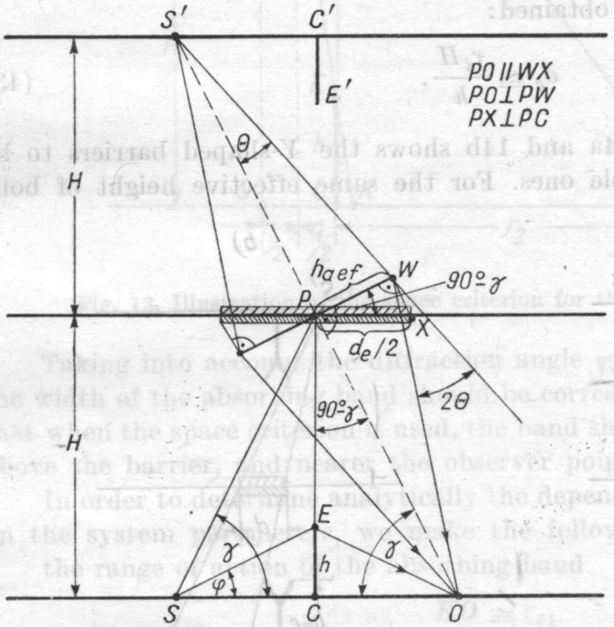

Fig. 15. Illustration of the energetic criterion for the case of a single reflection

at first, the discussion will be limited to the case where only one reflection from the ceiling is taken into account, the floor and other boundaries being absorbing;

the acoustic energy of the waves diffracted at both edges of the absorbing band is the same at the observation point for both paths (Fig. 15);

one half of the width of the absorbing band is replaced by the effective height of the barrier according to the formula

$$h_{aef} = \frac{d_e}{2}\sin\gamma; \tag{44}$$

the angle of diffraction 2θ at the edges of the absorbing band is small; according to the previously accepted criterion of 30° we can assume $\theta \cong 15°$ and then the approximate relation

$$\tan\frac{\theta}{2} \cong \frac{1}{2}\tan\theta; \tag{45}$$

in calculation it will be assumed that (6a) $M = 20N$, $M_a = 20N_a$, which is true only for $N > 1$ and $N_a > 1$. For $N_a < 1$ and $N < 1$ the relations $M_a = 20N_a + 3$ and $M = 20N + 3$ should be used (6b).

Having accepted these simplifications, we may, by (13), write the following relation for M_a:

$$M_a = 20N_a = \frac{20d_e \sin\gamma}{\lambda}\,\frac{\tan\theta}{\cos^2\theta}. \tag{46}$$

From Fig. 15 we find that

$$\tan\theta = \frac{h_{aef}}{H/\sin\gamma} = \frac{d_e \sin^2\gamma}{2H} \tag{47}$$

and thus

$$M_a = \frac{20d_e^2 \sin^3\gamma}{\lambda \cdot 2H}\,\frac{1}{\cos^2\theta}. \tag{48}$$

From expression (13) we also obtain

$$M = 20N = \frac{20 \cdot 4h \tan(\varphi/2)}{\lambda \cos^2\varphi}. \tag{49}$$

Substituting expressions (48), (49) and (33) into (35) and taking into account that

$$\operatorname{ctg}\gamma = \frac{r}{H}, \tag{50}$$

we have

$$\eta_a = \frac{16\beta h r^2 \tan(\varphi/2)\cos^2\theta}{H d_e^2 \sin\gamma \cos^2\varphi}, \tag{51}$$

whence

$$d_e = \frac{4r\cos\theta}{\cos\varphi}\sqrt{\frac{h}{H}}\sqrt{\frac{\beta}{\eta_a}}\,\frac{\tan(\varphi/2)}{\sin\gamma}. \tag{52}$$

Further reduction of formula (52) can be made for the following conditions: $H \gg r$ (thus $\sin\gamma \cong 1$) and $\varphi = \theta < 60°$; then

$$\tan\frac{\varphi}{2} = \frac{1}{2}\tan\varphi \cong \frac{1}{2}\,\frac{h}{r} \tag{53}$$

and $\cos\theta/\cos\varphi \cong 1$.

Hence we obtain an approximate formula

$$d_e \cong 2h\sqrt{\frac{2r}{H}}\sqrt{\frac{\beta}{\eta_a}}. \tag{54}$$

Assuming $\eta_a = 1$ (which means that $\Delta IL_a = 3$ dB) and $\beta = 1$, we get

$$d_e \cong 2h\sqrt{\frac{2r}{H}}. \tag{55}$$

Comparing this relation with relation (43) for the width d_g we see that their character is contrasting with respect to h and H. This is caused by the previously mentioned differences in the assumptions of the two criteria. In the case of the spatial criterion a higher barrier provides a greater region of shadow against the reflected wave. Hence, the width of the absorbing band can be smaller.

In the case of the energetic criterion, an increase in the height of the barrier causes a reduction in the effect of the diffracted wave and thereby makes the requirements for the reduction of the effect of the reflected waves more rigorous. This leads to the necessity of increasing the width of the absorbing band.

Similar reasoning can be carried out in order to examine the influence of the height of the hall. In the case of the spatial criterion an increase in hall height increases the area of action of the reflected waves for a given barrier height, thus requiring a larger width of band. However, as the hall height increases the reflected wave energy decreases and, according to the energetic criterion, this permits a reduction in the width of the absorbing band.

In both cases an increase in the distance of the source from the barrier makes an increase in the width of the band necessary.

The above discussion shows that in practice the spatial criterion would be applied for the reduction of the overall noise level in a hall, while the energetic criterion serves for noise level reduction at a selected working place, not far behind the barrier.

Substituting relations (51) and (49) into (37) and next into formula (32), we can calculate the barrier effectiveness in the reflected wave field when the effect of the waves is limited by means of an absorbing band. For a symmetrical situation of the barrier between the source and the observer we obtain

$$IL_{dra} = 10\log\frac{80h\tan\dfrac{\varphi}{2}}{\cos^2\varphi} - 10\log\frac{1+\dfrac{16\beta hr^2\tan(\varphi/2)\cos^2\theta}{d_e^2 H\sin\gamma\cos^2\varphi}}{1+\dfrac{\lambda\beta r^2\cos^2\theta}{20Hd_e^2\sin\gamma}}. \tag{56}$$

In order to account for multiple reflections between the ceiling and the floor, let us introduce, besides the simplifying assumptions accepted for determining the coefficients m_i and η_a given for relations (33) and (35), the additional assumptions:

the angle θ_i does not change much for image sources of higher order so that $\cos\theta_i$ does not depend on i;

the effective height corresponding to half of the width of the absorbing band does not depend on the order of the image source.

Then $M_{ai} = M_a = \text{const}$ and (35) becomes

$$\eta_{as} = \frac{2M}{M_a}\sum_{i=1}^{\infty}\frac{m_i}{\varepsilon_{ai}}. \tag{57}$$

From (29) and (57) and the condition $H \gg r$ we obtain

$$\sum_{i=1}^{\infty}\frac{m_i}{\varepsilon_{ai}} \cong (1+\beta)^2\left(\frac{r}{H}\right)^2\sum_{i=1}^{\infty}\frac{\beta^{2i-1}}{i^2}\frac{1}{\varepsilon_{ai}}. \tag{58}$$

For higher values of i the ratio $\beta^{2i-1}/i^2 \to 0$. Since.

$$\sum_{i=1}^{\infty}\frac{1}{i^2} \cong \frac{\pi^2}{6} \cong 1{,}64, \tag{59}$$

we can write

$$\eta_{as} < 3{,}28\,\frac{M}{M_a}(1+\beta)^2\left(\frac{r}{H}\right)^2. \tag{60}$$

Taking into account only the first reflection, a value for η_a can be obtained from expression (35) as

$$\eta_a = \frac{2M}{M_a}\left(\frac{r}{H}\right)^2. \tag{61}$$

Thus the increase of the coefficient η_a, caused by the effect of multiple reflections, is equal to

$$s = \frac{\eta_{as}}{\eta_a} < \frac{1{,}64(1+\beta)^2}{\beta}. \tag{62}$$

Putting (62) into formula (37) allows us to evaluate the increase of the effect of the reflected waves due to multiple reflections. From (62) for $\beta = 1$ we obtain $\sqrt{\eta_a} = 0{,}39\sqrt{\eta_{as}}$, which by virtue of (54) gives an increase in the width of the absorbing band of a factor of 2.5. In some cases instead of increasing the width of the band on the ceiling the use of an additional band on the floor may be preferable. Examination of this case is beyond the scope of the present paper, although it was tested experimentally.

When several noise sources are installed in different regions of the room, the screening of each source can be considered individually using the mirror method. When a large number of sound sources is installed in the room the reverberation method is preferable.

8. Experimental results for reflected wave field conditions

Three series of measurements were carried out:

(a) An investigation of the influence of the width of an absorbing band on the effectiveness of the barrier when the ceiling was reflecting.

(b) An investigation of the effectiveness of the absorbing bands when both the ceiling and the floor were reflecting.

(c) An investigation of the effectiveness of the Y-type barrier.

(a) Examination of the effect of the band width of the absorbing band was carried out on a 1 : 8 scale model.

In model the sound absorbing material was mounted on the ceiling. The remaining surfaces were absorbing. The width of the absorbing band was changed from 10 to 140 cm.

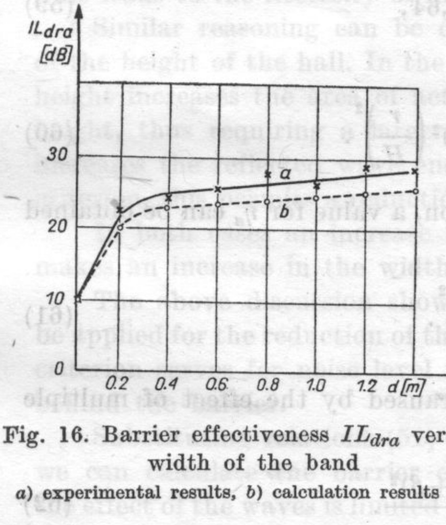

Fig. 16. Barrier effectiveness IL_{dra} versus width of the band

a) experimental results, *b*) calculation results

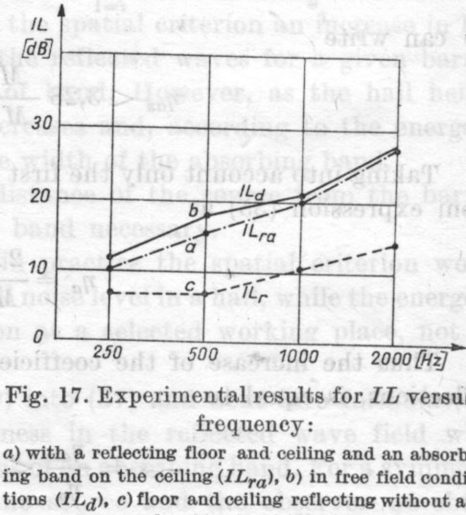

Fig. 17. Experimental results for IL versus frequency:

a) with a reflecting floor and ceiling and an absorbing band on the ceiling (IL_{ra}), *b*) in free field conditions (IL_d), *c*) floor and ceiling reflecting without an absorbing band (IL_{dr})

Measured parameters: height of room $H = 80$ cm, effective height of barrier $h_{ef} = 20$ cm, distance between source or microphone and the barrier in a symmetrical arrangement $r = 20$ cm, reflection coefficient of the ceiling without band $\beta = 1$, coefficient of reflection from absorbing band $\beta_a \cong 0$.

Measurements were performed at a frequency of 8000 Hz which corresponds to 1000 Hz in reality. Fig. 16 presents the analytical results according to (56) and the measured results. The results show that the measured values of ΔIL_{dra} (curve *a*) are somewhat higher than those calculated (curve *b*).

The value of the width of the absorbing band (calculated from (55)), at which the barrier effectiveness should decrease by 3 dB in relation to anechoic conditions, is equal to

$$d_e = 2 \cdot 20 \sqrt{\frac{2 \cdot 20}{80}} = 28.3 \text{ cm}.$$

For a smaller width, namely for $d_e = 20$ cm, the experimental results show a drop in the ΔIL_{ra} of the barrier by 3 dB relative to anechoic conditions. Thus the measured results are better than the analytical ones.

(b) Measurements were carried out on a 1 : 8 scale model with two reflecting surfaces – the ceiling and the floor – on which absorbing bands were placed.

Measuring parameters: $H = 80$ cm, $r = 20$ cm, $h_{ef} = 20$ cm.

The width of the band d_e calculated from (55) for a single reflection from

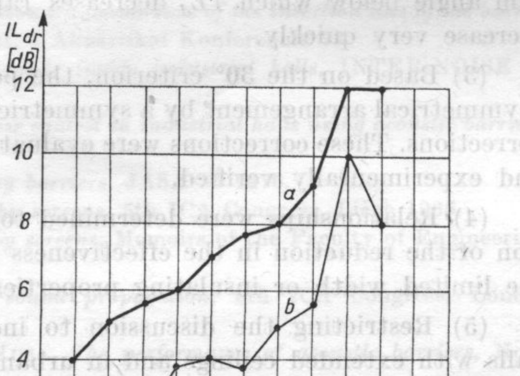

Fig. 18. Experimental results for IL_{dr} of a *Y*-shaped barrier (curve *a*) and a straight barrier (curve *b*) as functions of frequency

ceiling, with a single band, was $d_e = 28,3$ cm. The tests were carried out for $d_e = 30$ cm. The experimental results were compared with the results for a free field, with the ceiling and floor totally silenced (curve *b*) as well as with the results when the absorbing bands were removed, i.e. with totally reflecting floor and ceiling surfaces (curve *c*). The results obtained indicate that the performance of the bands is completely satisfactory (Fig. 17).

(c) Comparative measurements of the effectiveness of *Y*-shaped barriers with the same effective height were carried out as initial measurements for further investigations.

Measurements were made in a room with all the walls reflecting. Measuring parameters: room height $H = 2.5$ m, effective height of barrier $h_{ef} = 34$ cm, length of the arms of the Y-barrier $l = 20$ cm. Distance between loudspeaker or microphone and barrier $r = 34$ cm. Fig. 18 illustrates the results obtained. They indicate that the properties of the Y-barrier are better than those of straight barriers and suggest that further investigations in this direction should be made.

9. Conclusions

(1) From the theoretical analysis and data of diagrams in references, which have been confirmed by experimental results, it is necessary to introduce into the formulae for IL_d a correction for the sphericity of the waves. This approximates real conditions but still requires a more detailed study.

(2) Analysis of the curves of IL_d vs. diffraction angle ψ showed that it is helpful to introduce a 30° criterion constituting a limiting value for the diffraction angle below which IL_d decreases rapidly and above which it does not increase very quickly.

(3) Based on the 30° criterion, the possibility was shown of replacing an asymmetrical arrangement by a symmetrical one by the introduction of suitable corrections. These corrections were evaluated, presented in the form of diagrams and experimentally verified.

(4) Relationships were determined to permit the quantitative determination of the reduction in the effectiveness of the barrier in a free field, due to the limited width or insulating properties of the barrier.

(5) Restricting the discussion to individual noise sources in industrial halls with extended ceilings and in urban areas, the method of image sources was extended to a mirror method. In this method the image barriers and band-barriers are treated as barriers against image sources.

(6) Analysis of the performance of an absorbing band, using the mirror method, permitted the proposal of a hypothesis to consider the absorbing band as a barrier against image sources. This hypothesis requires further development but it has permitted the presentation of an analytical method which gives quite good agreement between the analytical and the measured results.

(7) Based on the analytical method developed, relationships for the choice of the width of the absorbing bands were determined according to two different criteria: a spatial criterion and an energetic criterion. From a practical point of view these criteria concern respectively:

— the screening of a wide area behind the barrier ignoring energetic considerations,

— the screening of a certain area of the acoustic field not far behind the barrier with a given ratio of the energy of the reflected waves to that of waves diffracted by the barrier.

(8) The theoretical discusion was supported by experiments in real and model conditions. The experimental results in general gave values somewhat higher than the analytical ones.

(9) The mirror method developed and used in the paper, despite the introduction of far-reaching simplifying assumptions, permits a good assessment, comparing graphical and analytical methods, of the conditions restricting the reflected waves which reduce the effectiveness of a barrier.

(10) The simplified relationships may be used:

(a) in the desing of industrial interiors to determine conditions suitable for the joint action of barriers together with absorbing bands,

(b) in the design of urban areas by using the criterion of 30°.

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