Improvement of barrier efficiency by shape modifications

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1. Introduction

It is generally recognized that the primary factor limiting the barrier efficiency for reducing noise is the wave diffraction at the top of the wall. Often the surface of the wall is treated with absorptive material, and the diffraction is somewhat reduced, thereby increasing the barrier efficiency. However, it has been recognized that the proper choice of the barrier top shape could increase the barrier efficiency considerably. Various shapes have been proposed, including T-shape, Y-shape, U-shape and thick wall, the last one actually representing the building or earth berm. Still the double-wall barrier is most preferred over any other shape, and considerable work has been devoted in to determine its real advantage[1,2]. However, the use of double-wall system is often too costly, and sometimes the site topolozy may not permit easy installation of such system.

The purpose of this study is to develop alternative shapes to the double-wall system, which costs less while preserves the same efficiency as the double-wall. In fact, the Y-shaped and U-shaped barriers may be regarded as such alternatives. However the width and the depth of the shape must be chosen properly if it were to produce similar efficiency as the double-wall. In this study, the range of proper depth of the U-shaped barrier was determined in relation with the width based on the wave theory of diffraction and reflection. The results were then compared with the experimental results. The two were found to be in good agreement. Also the improved perfermance of double-wall, as compared to the single wall, was demonstrated both theoretically and experimentally.

2. Theoretical development of double-wall diffraction

The theory of double-wall diffraction may be formulated based on the single-wall diffraction theory. Pierce[3] developed an analytical formulation of wave field diffracted by the wedge-shaped boundary by using a contour integral in complex plane. His integral formulation takes a numerically solvable asymptotic form when the source and the receiver are located at distances large compared to a wavelength from the wedge edge. For the case of a point source, the asymptotic approximation takes the following form.

$$P_{diff} = \frac{e^{ik(r_s + r)}}{r_s + r} \frac{e^{i\pi/4}}{\sqrt{2}} \left[A_d(X_+) + A_d(X_-)\right] \tag{1}$$

$$A_d(X) = \mathrm{sign}(X) \left[f(|X|) - ig(|X|)\right]$$

Here f(X) and g(X) are the auxiliary Fresnel functions, and the parameters $X_{\pm}$ are determined by the coordinates of the source and the receiver as well as the wedge angle. It is not intended to give their full expressions here. However, in the limiting case of zero wedge angle, i.e., a thin screen, they take the following simple forms.

$$X_{\pm} = -2 \sqrt{\frac{2r_s r}{\lambda(r_s+r)}} \cdot \cos\frac{\theta_o \pm \theta}{2} \tag{2}$$

Here λ is the wavelength, and Fig. 1 shows the coordinate relations used in this paper. We limit the case to the two-dimensional problem in which both the source and the receiver are in a plane intersecting with the wall normally. However, this can be readily extended to the more general case of arbitrary source and receiver locations as treated by Pierce.

The parameter X may be understood as an indicator of the proximity of the receiver to the shadow boundary. For large X, that is, when the receiving point is well within the shadow region, Eq. 1 leads to the Keller's formulation, however, Eq.1 displays a functional continuity crossing the shadow-boundary. This is a desirable property in dealing with the double-wall since, as will be shown, the acoustic behavior of a double-wall is determined by wave components both in the shadow region and at the shadow boundary.

Fig. 2 shows several possible wave paths inside the double-wall with a finite depth. It should be noted that if the depth becomes infinite, only the primary wave exists. It is the purpose of this paper to assess the effect of finite depth as compared to the infinite case. Although only the two lowest orders of reflections are shown in Fig. 2, there could be an infinite number of such reflections, of which i-th order of reflected

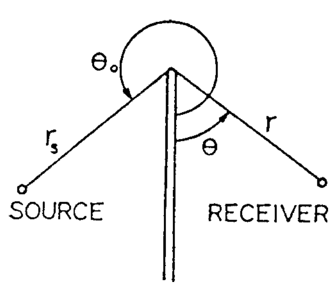

Fig. 1. Single-wall coordinates.

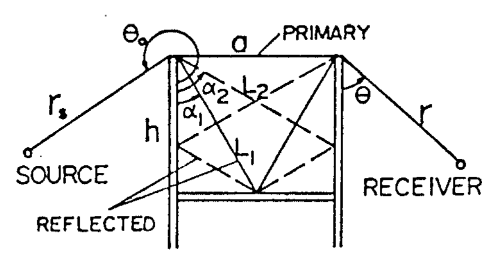

Fig. 2. Propagation paths in a double-wall.

wave propagates an effective path-length given as follows.

$$L_i = \sqrt{(2h)^2 + [(2i - 1)a]^2} \tag{3}$$

The primary wave path-length inside the double-wall is denoted by $L_0 = a$. Both the primary and the reflected waves are diffracted by the second wall once again before reaching the receiving point. Such secondary diffractions can be treated by a similar fashion as for the single-wall case discussed by Eq. 1, except now that the incident wave itself is a diffracted one. The original point source, upon diffracted by the first wall, forms an equivalent line source along the top of the first wall, each point of which may be regarded as a point source. Thus the individual wave path inside the double-wall undergoes another diffraction by the second wall before reaching the receiving point, and the total field at the receiver may be expressed as the summation of doubly diffracted wave components.

$$P = \sum_{i=0}^{\infty} P^{\text{double}}(r, \theta) = \sum P_I \frac{e^{i\pi/4}}{\sqrt{2}} [A_d(BY_+) + A_d(BY_-)]$$

$$P_I(r, \theta) = \frac{e^{ik(r_s+L+r)}}{r_s+L+r} \cdot \frac{e^{i\pi/4}}{\sqrt{2}} [A_d(X_+) + A_d(X_-)]$$

$$X_\pm = -2\sqrt{\frac{2r_s(L+r)}{\lambda(r_s+L+r)}} \cdot \cos\frac{\theta_0 \pm \alpha}{2} \tag{4}$$

$$Y_\pm = 2\sqrt{\frac{2(r_s+L)\, r}{\lambda(r_s+L+r)}} \cdot \cos\frac{\theta \mp \alpha}{2}$$

$$B = \sqrt{\frac{L\,(r_s+L+r)}{(r_s+L)(r+L)}}$$

The primary wave (i=0) corresponds to $L_0 = a$ and $\alpha_0 = \frac{\pi}{2}$, and represents the biggest contribution.

3. Numerical results and experiment

Eq. 4 represents the asymptotic approximation of the double-wall diffracted wave field, and is in a readily solvable form by a digital computer. As the reflection order becomes higher, the diffraction angle decreases (Fig. 2). Thus, apart from the primary wave, the series in Eq.4 initially diverges due to the increased amount of diffraction with the decreasing diffraction angle. However, for still higher orders of reflection, the propagation distance given by Eq. 3 becomes sufficiently large, and the decrease in wave strength due to this becomes more important than the increasing diffraction, eventually resulting in a convergence of the series. When 100% of reflection by the walls and the bottom is assumed, the convergence begins to take place around the 8-th order of reflection for the case of geometry discussed below. However, in order to increase the converging efficiency as well as to simulate the more realistic case, we assumed 99% of reflection in this study. It should be noted that the commonly used cement structure has typically several percent of sound absorption characteristics for most of the frequency range of traffic noises.

Fig. 3a shows the relative deviation of the wave strength, as compared to the infinitely deep couble-wall case, for various values of the depth to

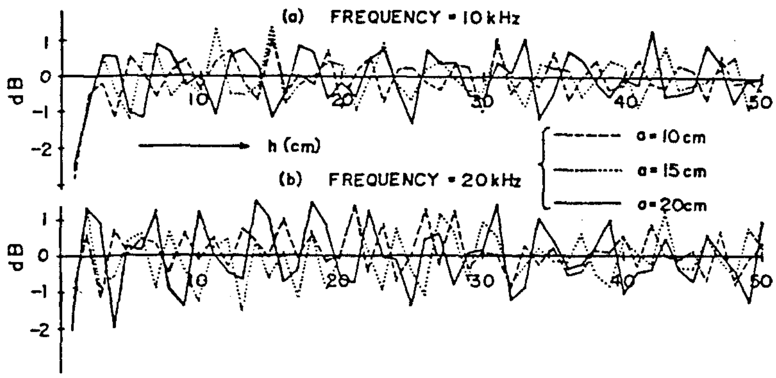

Fig. 3. Relative deviations of IL of double wall with finite depths as compared to infinitely deep case.

the bottom. The frequency, as well as the wall geometry, were chosen such that they would permit the comparison of the numerical results with the scale-model experimental results discussed later. Three curves in this figure correspond to three different values of double-wall separation. The fluctuations occur mainly because of the interference between the primary and the reflected waves. The zero deviation corresponds to the infinite depth, and all the curves show a general tendency of decreasing deviation with increasing depth, indicating that they will eventually approach to the zero deviation as would be expected. It is also noted that the curve for smaller separation of walls displays less deviation. Generally speaking, however, deviations can be said to be within ± 1 dB for the range of depth larger than the separation of the corresponding double-wall. This conclusion may not be generalized to other frequencies. For example, Fig. 3b represents similar curves for 20 kHz wave, displaying singnificantly larger fluctuations than the previous one. Since the net effect of double-wall diffraction and reflection depends not only on double-wall geometry, but also on the source-receiver relations, any simple conclusion as to the frequency effect on the double-wall performance may not be possible. At this point, we can only conclude that the acoustic property of an infinitely deep double-wall may well be approximated by the same wall with the depth larger than the separation of the walls within ± 1 dB for most of the frequency range of interest.

A scale-model experiment was performed to verify the theory. A 30 cm high model-barrier, with 10 cm separation between walls, was constructed with 9 mm thick gypsum board, and was installed inside a large anechoic chamber. Both the source and the receiver sides of the floor were covered with the gypsum board as well in order to simulate the actual ground conditions. It was found that the gypsum board we used has an absorption coefficient of about 0.01 for the frequency range employed in this study, namely between 3 kHz and 20 kHz. A point source was constructed using a stainless cone and pipe. Fig. 4 shows the experimental set-up schematically.

The measuring microphone was installed on a rail carriage, allowing the continuous measurements of spatial distribution of sound. Fig. 5 shows an example of measurement taken at a fixed position, while sweeping frequencies, for three different depths to the bottom. This figure represents the relative deviation of barrier insertion loss for each of the finite depth as compared to the reference depth case, which is 30 cm deep. It is noted

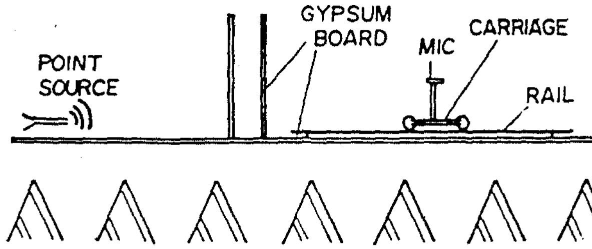

Fig. 4. Schematic diagram of experimental set-up

that apart from the frequency-depending small fluctuations, the deviations for the 20 cm and 10 cm depth cases are clustered around the 0 dB abscissa, meaning that the double-wall performance is practically independent of the depth as long as the bottom is deeper than the separation of the walls. On the other hand, the double-wall structure with no depth, i.e. a thick wall, reveals somewhat reduced insertion loss as compared to the hollow structure. This is mainly due to the increased efficiency of diffraction around the flat top surface.

For the completeness of the study, we compared the double-wall performance with that of the single-wall, both theoretically and experimentally. Fig. 6a shows the measured excess insertion loss defined by

$$\Delta IL = IL\ (\text{double-wall}) - IL\ (\text{single-wall}) \qquad (5)$$

Fig. 6b shows corresponding values obtained theoretically. Apart from small peaks appearing in Fig. 6a, these two figures show a remarkable similarity in their general characteristics. Especially the periodically appearing large peaks and dips (indicated by arrows in the figures) are almost exactly coinciding, and they actually represent the constructive and destructive interferences between the direct and ground-reflected waves. Because of such interferences, the double-wall performance appears to be inferior to the single wall performance in some frequency ranges where the excess insertion loss becomes negative. However, this is not the

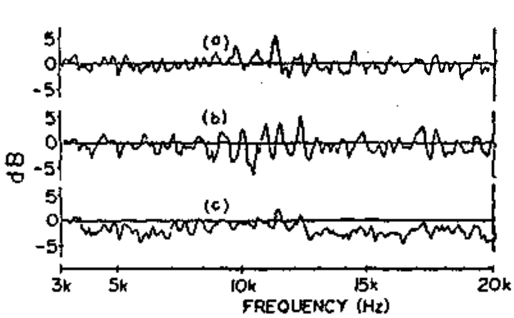

Fig. 5. Relative deviations of insertion loss of double-wall with three different depth(h) compared to that of 30 cm depth. (a) h = 20 cm, (b) h = 10 cm, (c) h = 0 cm.

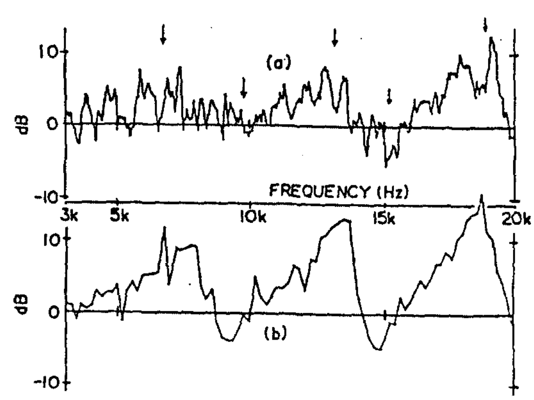

Fig. 6. Excess insertion loss of double-wall over single-wall. (a) Measured result, (b) Calculated result.

(The source and receiver are located at distance of 1.5 m from the barrier respectively) intrinsic problem of the double-wall system, and it can be said that for the geometry employed in this study, double-wall displays at least 5 dB higher insertion loss than that of the single-wall. The lack of the small peaks in Fig. 6b, as compared to Fig. 6a, is simply because the frequency increment was taken with a finite step in numerical analysis. Taking this fact into account, we conclude that the double-wall theory developed here can well be used in predicting the barrier performance in actual situations.

4. Conclusion

The double-wall theory developed in this study, based on the single-wall diffection theory as well as on the geometrical reflection theory inside the double-wall cavity, has proved to be a reliable analytical tool in predicting barrier performance in actual situations. The theory was used in establishing a working relation between the wall separation and its depth. It was shown that the depth to the bottom comparable to the wall separation would be sufficient in preserving the performance of the double-wall structures. Thus, for example, instead of constructing 3 m high two walls, one may construct a 2 m high single-wall with a 1 m wide and 1 m deep U-shaped structure on top of it. This would save a considerable cost in both material and installation.

One problem inherent to the barrier is that it may aggravate noise problem for certain frequency ranges due to the constructive interference between the direct and the ground-reflected waves. Our study showed that the double-wall barrier can alter the interference pattern considerably, to the extent that for some frequency ranges, the double-wall performance is actually worse than that of the single-wall. This finding suggests the possibility of preventing the important frequency portion of the noise from falling into the constructive interference region, or even improving the insertion loss by effectively shifting the frequency band to the destructive interference region, by proper choices of double-wall geometry.

A major factor we did not considered in this study is the air absorption. This may modify the analytical results somewhat. However, it is believed that the general conclusion of this study should still be valid.

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