Performance Analysis of the Wave Trapping Barrier

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ABSTRACT

The design of a noise barrier for reducing unwanted noise is a common practice in acoustical engineering. However, when the barrier is placed in front of the source with large reflective surface, multiple reflections between the source and barrier happen and significantly reduce the noise reduction performance of the barrier. In order to minimize this deterioration effect, the Wave Trapping Barrier (WTB), which has a designed surface profile and resonance sound absorption, has been developed. The designed surface aims to change the direction of the reflective noise and thereby trap them within the domain bounded by the source surface and noise barrier. In this paper, the performance of WTB is numerically investigated and compared with T-shape and Tilted barriers. It is found that a WTB with absorption material on its surface achieves the best result. We also underline the mechanism involved in the improved performance of the WTB.

1. INTRODUCTION

A sound barrier is an effective tool in solving environment noise problems. In general, the noise barrier is placed at the location between the source and receiver to avoid the direct sound wave approaching the receiver. An empirical formula to predict the noise barrier performance based on extensive experimental measurements has been given by Maekawa (1968). This formula is easy to use and becomes a rough tool of design in a wide range of noise abatement engineering projects. On the other hand, a more accurate analytical model was proposed by Pierce (1973), and the discrepancy between his model and the empirical model by Maekawa is discussed. Since then, many efforts have been made to design a more efficient noise barrier in both experimental and numerical ways. A comprehensive review of these studies can be found from Li (2005). In fact, when there is a large reflecting surface placed on the opposite of the barrier, multiple reflections occur. An experimental study by Watts (1996) shows, that the multiple reflections significantly degrade the barrier performance. In his study, the Insertion Loss (IL) of a noise barrier with 2m height is reduced by 4 dB (A) if a reflecing wall with same height is erected at the opposite. As a solution, it is suggested to use absorption material and tilted barrier to reduce this deterioration. The effect of different shapes of noise barrier to minimize the deterioration impact is studied by Monazzam and Fard (2011). The comparison suggested that a tilted barrier with a 10° slope is the best option. Indeed, the tilted barrier redirects the sound wave upward which reduces the wave diffraction at the barrier edge. In the same principle, a Wave Trapping Barrier (WTB) is proposed by one of the authors and his colleagues (Pan *et al.* 2004). The WTB has a profile of multiple wedges on its surface. The wedges redirect reflection waves downward to the ground so that the waves are trapped within the barriers bounded domain. The superiority of WTB over conventional noise barrier has been experimentally validated in the Willowdale mining site of WA (Pan *et al.* 2004). However, there lacks of an insightful view of the underlying physics. The work presented here is an extension study of WTB. The mechanism of how the multiple reflections deteriorate the noise barrier is discussed and a guideline is given for the design of a more efficient WTB.

2. BOUNDARY ELEMENT METHOD (BEM) FOR WTB PERFORMANCE

The empirical formula and analytical method provide efficient tools to predict the performance of noise barrier with simple configurations. When the barrier profile is complex, these methods become less effective and the BEM method always becomes the option. Assuming a noise barrier with arbitrary shape is erected on the ground, the harmonic time dependence sound field generated by a source is the solution of inhomogeneous Helmholtz equation (Fahy and Gardonio 2007):

$$\nabla^2 p(r) + k^2 p(r) = Q(r). \quad (1)$$

where ∇^2 is the Laplace operator, k is the wave number, $p(r)$ is the sound pressure at r, $Q(r) = A\delta(r-r_s)$ is the sound source locates at r_s with amplitude of A. For the simplicity of the problem, a 2D model is employed throughout. In order to evaluate the sound pressure $p(r)$, the following boundary conditions should be satisfied:

(1) At infinite far field,

$$\lim_{r\to\infty}\left(\frac{\partial p(r)}{\partial r} - ikp(r)\right) = O\left(\frac{1}{\sqrt{r}}\right). \text{ (Sommerfeld condition)}$$

(2) At boundaries,

$$\begin{cases} \dfrac{\partial p(r)}{\partial n} = 0, \text{(for rigid boundary)} \\ \dfrac{\partial p(r)}{\partial n} = -\mathbf{i}\omega\rho_0 v(r) Z(r), \text{(for absorptive boundary)} \end{cases}.$$

The sound wave equation and the associated boundary conditions can be solved using the boundary element method. Using the solved sound pressure response to the source excitation, the performance of noise barriers, in terms of noise Insertion Loss (IL), is evaluated.

3. PERFORMANCE DETERIORATION DUE TO MULTIPLE REFLECTIONS

The effect of the reflecing wall on the insertion loss is examined by comparing IL of barrier with and without the reflecing wall (Fig. 1). When the wall is placed at the opposite side of the barrier, significant barrier deterioration is observed. The IL curve of barrier with reflecing wall demonstrates an oscillating behavior with many peaks and dips. Particularly, some negative ILs are found at the dips indicating the sound pressure at receiver increases due to the presence of the reflecing wall.

In order to have a better view of how the barrier is affected by the reflecing wall, the sound pressure distributions at the first five dips of the IL curve are drawn in Fig. 2. At each frequency, a clear and regular resonance feature can be identified within the domain bounded by the reflecing wall and barrier. In fact, these dips correspond to the resonances of the trapped modes in the current configuration. According to Ursell (1951), a mass of fluid bounded by fixed surfaces and by a free surface of infinite extent may be capable of vibrating under gravity in a mode (called a trapping mode). The potential energy decays with the increase of distance toward infinite extent but local oscillation with strong energy are trapped in the domain bounded by fixed surfaces. The local oscillation yields a clear and regular resonance feature and therefore, the pressure distributions between the barrier and reflecing wall at these frequencies are similar to the (2,0), (4,0), (6,0), (8,0) and (10,0) modes of a rigid-wall rectangular cavity with the same dimension. On the other hand, these local resonances increase the particle velocity and sound pressure at the top region of the barrier and then increase the sound pressure at the receiver location.

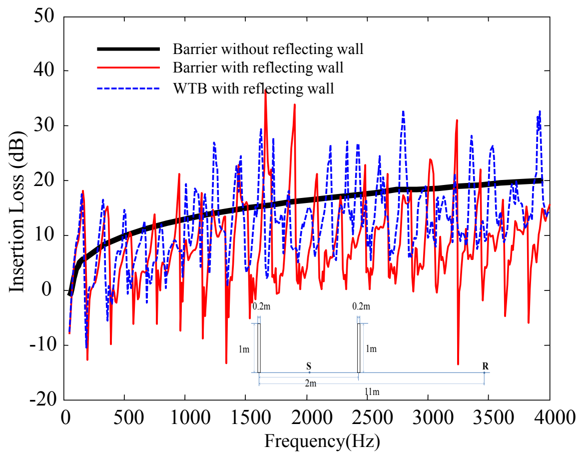

Figure 1 Insertion Loss (IL) of single rectangular barrier, double rectangular barriers and WTB at right side barrier.

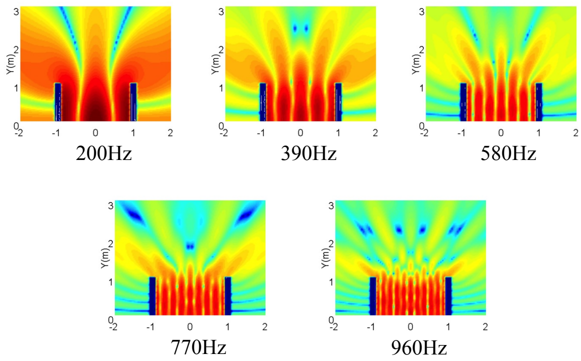

Figure 2 Sound pressure distribution at first five dips of the Insertion Loss curve of double barriers.

For a rectangular cavity with all the boundaries rigid, the resonance frequencies of the even modes (with modal structure parallel to the ground) are

$$f_{(n,0)}=nc/2L, \quad (2)$$

where n is the horizontal mode index, c is the sound speed, L is the horizontal length of the cavity. The odd mode should also be excited if the source were placed at the corner between the barrier and ground. Nevertheless, although a sound source, placed in the middle line of the noise barrier and reflection surface, can only excite the even modes, adequate evidence is already obtained for demonstration of the effect of resonances on the IL. The configuration can be used for noise control at the resonances using different surface profiles and sound absorption.

The resonance frequencies of the horizontal modes are plotted in Fig. 3, and are directly corresponding to the resonances of the trapped modes of the current configuration. Compared with the resonance frequencies of a rigid-wall cavity (as shown in Fig. 3), the trapped mode resonances are slightly higher. Indeed, unlike the cavity with all boundaries rigid, the barrier and reflecing wall bounded domain has the top boundary free. In this case, the air mass becomes a finite value instead of infinite as it is in the rigid boundary cavity. As a result, the reduced boundary rigidity caused the increase in the resonances of trapped mode.

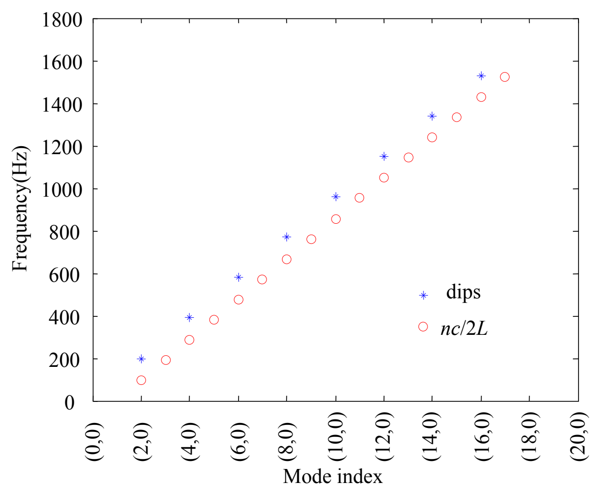

Figure 3 Resonances of rigid cavity and the dip frequencies in the IL curve of double barriers.

4. WTB PERFORMANCE

The performance of WTB is evaluated herein. As an illustration, the rectangular barrier at the right side is replaced by a WTB. The IL of this new profile is plotted in Fig. 1 and compared with others. When WTB is used, the overall insertion loss is improved due to the modified profile. The wedges on the barrier redirect the sound waves downward to the ground and trap the waves within the domain bounded by the barrier and reflecing wall.

For a better understanding of the WTB effect, the pressure distributions at the resonances of the trapped modes are examined. In Fig. 4, the resonance features are obvious at the first three frequencies. Based on the analysis in previous section, the resonance effect yields a poor barrier performance at the corresponding frequency. Therefore, no improvement is found around these three frequencies in Fig. 1 compared with rectangular barrier. At 770Hz and 960Hz, however, the resonance effects are no longer obvious. The pressure distributions are affected due to the change of barrier profile at the two frequencies. Compare with other three frequencies, 770Hz and 960Hz having small wavelengths. These wavelengths are comparable to the wedge size on the barrier and are more easily influenced by the modification of barrier profile. At low frequencies, the wavelengths are larger and are less sensitive to the change of barrier profile. As can be seen in Fig. 1, there is no improvement of WTB below 1000Hz, but impressive improvement is noticed after 1000Hz.

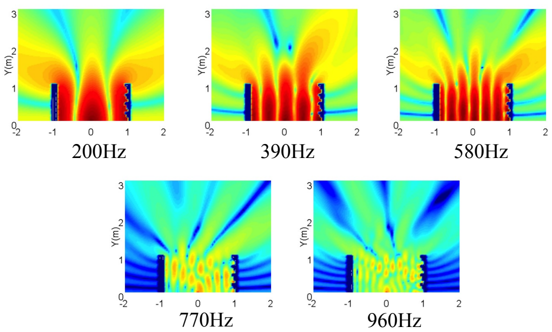

Figure 4 Sound pressure distributions at the dips of the Insertion Loss curve of double barriers with a WTB at the right side.

5. COMPARISON OF DIFFERENT BARRIER PROFILE WITH ABSORPTION MATERIAL

The performance of WTB is compared with T-shaped barrier and the Tilted barrier. The latter barrier having a tilting angle of 10° is the best solution to overcome the deterioration effect according to the work by Monazzam and Fard (2011). The configurations of the three barriers are drawn in Fig. 5. For each IL calculation, the corresponding type of barrier is replacing the rectangular barrier at the right side as is shown in Fig. 1. For a better comparison of barrier performance, a Mean Insertion Loss is defined as:

$$IL_{mean} = \frac{\sum_f IL(f)}{\text{number of } f}. \quad (3)$$

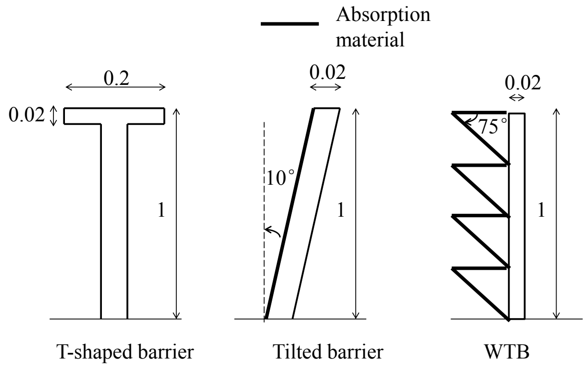

Figure 5 Configurations of T-shaped, Tilted and WTB barriers.

As shown in Fig. 6, all the IL curves present oscillation behavior. But the Tilted barrier and WTB have the small fluctuation range. Indeed, a mean IL of 8.2dB, 11.2dB and 11.2dB are obtained for the T-shape barrier, Tilted barrier and WTB, respectively. Both the Tilted barrier and WTB achives better performance than the T-shaped one. In terms of the working principle, both the WTB and Tilted barrier are redirecting the sound waves, but with different redirecting directions. The downward waves from WTB impinge on the ground or the lower part of WTB and may bounce upwards. In this case, if no absorption material is arranged on the WTB or ground, the sound waves may not be well trapped within the bounded domain.

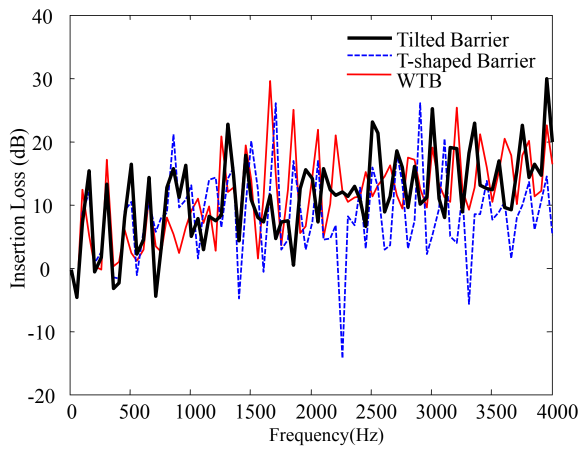

Figure 6 Insertion Loss of three different types of barriers.

With this concern, the influence of absorption material to the performance of Tilted barrier and WTB is studied. The absorption material coating is paved and indicated by the thicker lines in Fig. 5. The IL is examined at receiver 7 (R7) as the layout in Fig. 8.

In Fig. 7, when no absorption material is used (absorption coefficient = 0), Tilted barrier has a better performance. When absorption material is used, significant improvement can be found at WTB. In the presence of absorption material, sound intensity is dissipated every time when the wave impinging at the place where absorption material is used. The more reflections happen, the more energy is dissipated. When the absorption further increases, however, the mean IL of two types of barriers approaches to each other. For this case, the high absorption dissipates all the incoming wave energy and no reflection occur within the bounded domain.

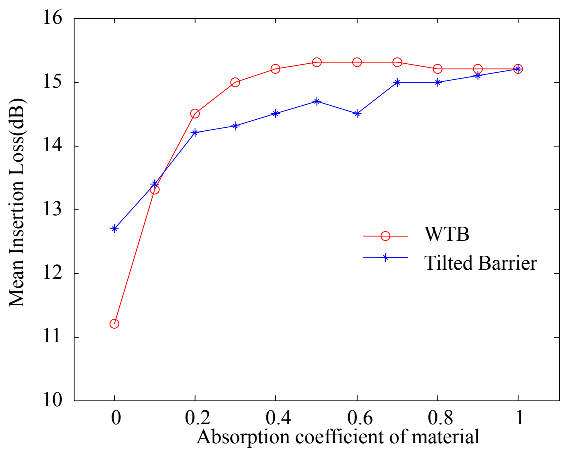

Figure 7 Mean Insertion Loss with respect to absorption material with different absorption coefficient.

As the last example, the Mean IL of Tilted barrier and WTB coated by the absorption material having coefficient of 0.5 are used and compared at 9 receiver locations (Fig. 8). The results are listed in Table. 1. Comparison shows that, WTB with absorption material provides better performance than the Tilted barrier when absorption material is used. Particularly at R1, a mean improvement of 1.4 dB is observed. This is because R1 is close to the illumination zone of the Tilted barrier. At other locations, WTB has an average of 0.5 dB better than Tilted barrier. In terms of practical installation, the wedge structure with absorption material coating is easier to install on the original barrier. But cumbersome work has to be done to replace the original barrier with a Tilted barrier.

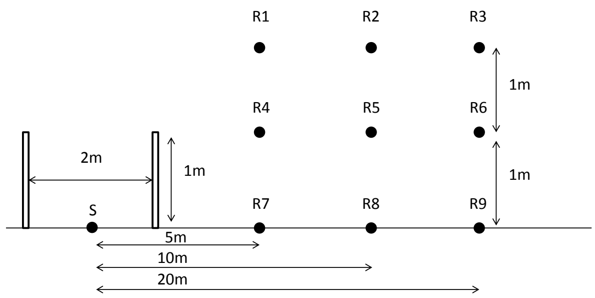

Figure 8 Schematic of source and receiver locations.

Table 1 Mean Insertion Loss in dB (left: WTB, right: Tilted Barrier)

R1		R2		R3	
10.1	8.7	14.2	13.4	15.8	15.5
R4		R5		R6	
17	16.3	17.4	17.1	16.8	16.1
R7		R8		R9	
15.3	14.7	13.4	13	12.6	12.1

6. CONCLUSIONS

The resonance effect of domain bounded by the barrier and the reflecing wall to the performance deterioration of the noise barrier is studied. At each resonance, strong multiple reflections happen and significantly degrade the barrier performance. These multiple reflections are actually happening at the resonances of the trapped modes in the barrier configuration. And due to the characteristics of trapped mode, the pressure distributions within the domain bounded by reflecting wall and barrier are similar to the ones of rigid cavity with the same dimension. The WTB is used to minimize the deterioration effect in the current work, and it is found that WTB is more efficient at high frequencies because the wavelength is more sensitive to the change of barrier profile at high frequencies. The performance of WTB is compared with T-shaped and Tilted barriers. If all the boundaries are rigid, the Tilted barrier and WTB obtain equal performance and are better than T-shaped barrier. When absorption material is used as the coating on the barrier, WTB has the best performance.

ACKNOWLEDGEMENT

The first author is grateful to the financial support of the Research Student Attachment Program in The Hong Kong Polytechnic University. Also, his special thanks will go to Dr. Hequn Min from Nanyang Technological University on his patient instruction on using Sysnoise software.

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