QUASI-PERIODIC NOISE BARRIER WITH HELMHOLTZ RESONATORS FOR TAILORED LOW FREQUENCY NOISE REDUCTION

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Abstract

Barriers are generally less effective at low frequencies due to easier diffraction of long acoustic wavelengths over the top edge of a barrier. The effectiveness of a barrier is also highly dependent on its design. This paper examines the acoustic performance of a noise barrier embedded with Helmholtz resonators along the top edge of the barrier using a quasi-periodic boundary element technique. Using the quasi-periodic approach, the length of a nominally infinitely long barrier is truncated using a finite number of periodic sections. A Helmholtz resonator tuned to a specific low frequency is included in each periodic section of the barrier. High insertion loss at the tuned frequency is observed. Compared to insertion loss results for an equivalent straight barrier in the absence of the embedded Helmholtz resonators, greater attenuation in the barrier shadow zone at the tuned frequency can be achieved.

1. Introduction

Road traffic is a major source of noise in urban areas. Identification of the dominant frequencies emitted by traffic noise is important before effective noise control can be successfully achieved. Torija and Ruiz [1] showed that the frequency bands having the highest correlation with urban traffic flow occur between 50 and 400 Hz. The fundamental modulation frequency of engine brake noise from heavy vehicles has been described as being one of the greatest source of community complaints [2].

Barrier designs have been developed to target the low frequency range. Monazzam and Lam [3] reviewed a range of barrier designs and showed that adding a diffuser on the top of a 3 m high T-shaped barrier can increase the performance of the barrier at certain frequencies. Incorporating cavities or resonators in barrier designs to attenuate noise at particular frequencies have also been investigated [4-5]. High levels of attenuation were presented for a wave-trapping barrier by Pan et al. [6]. The wave-trapping barrier comprised of multiple wedges with perforated surfaces, a back cavity and an internal lining, and was shown to significantly reduce the sound pressure level at low frequencies.

In a two-dimensional noise barrier model, the length of a barrier is extended to infinity [4,6-9]. However, a three-dimensional model is required for barrier geometries that do not have constant cross section in the third dimension. To reduce the computational time and storage requirements to solve a three-dimensional barrier model, a quasi-periodic boundary element method (BEM) was recently developed by the authors [10]. In this paper, the quasi-periodic BEM technique is used to predict the acoustic performance of a noise barrier with an array of Helmholtz resonators distributed along the top surface of the barrier. The effectiveness of the barrier is improved in a narrow frequency band by tuning the Helmholtz resonators to a certain frequency. The insertion loss of a noise barrier with embedded Helmholtz resonators tuned to a single frequency is compared to the insertion loss of an equivalent straight noise barrier in the absence of the Helmholtz resonators.

2. Numerical Model of a Quasi-Periodic Noise Barrier

Assuming a time harmonic dependence of the form $e^{-i\omega t}$, the Helmholtz equation is given by

$$\Delta p(\mathbf{x}) + k^2 p(\mathbf{x}) = 0 \tag{1}$$

where $p(\mathbf{x})$ is the acoustic pressure at a field point $\mathbf{x}$, k is the acoustic wave number, ω is the angular frequency and $i = \sqrt{-1}$ is the imaginary unit. The fluid particle velocity v which is the normal derivative of the acoustic pressure p is defined by

$$v(\mathbf{y}) = \frac{1}{i\omega\rho}\frac{\partial p(\mathbf{y})}{\partial n(\mathbf{y})} \tag{2}$$

where ρ is the fluid density. The vector $n(\mathbf{y})$ represents the outward normal at the surface point of the structure $\mathbf{y}$ and $\partial/\partial n(\mathbf{y})$ is the normal derivative. Equation (2) can be rewritten in terms of a boundary integral equation using the Green's function $G(\mathbf{x},\mathbf{y})$ [11]. Consideration of source terms $p_{\mathrm{p}}(\mathbf{x})$ yields

$$c(\mathbf{x})p(\mathbf{x}) + \int_{\Gamma} \frac{\partial G(\mathbf{x},\mathbf{y})}{\partial n(\mathbf{y})} p(\mathbf{y}) d\Gamma(\mathbf{y}) - \int_{\Gamma} i\omega\rho G(\mathbf{x},\mathbf{y})\, v(\mathbf{y}) d\Gamma(\mathbf{y}) = p_{\mathrm{p}}(\mathbf{x}) \tag{3}$$

$c(\mathbf{x})$ represents a constant coefficient and is equal to 1 for points in the acoustic domain, 0 for points outside the acoustic domain and 0.5 on a smooth boundary Γ [11]. $p_{\mathrm{p}}(\mathbf{x})$ is the incident pressure as a result of the acoustic source. Discretisation of Eq. (3) leads to the following linear system of equations [11]

$$\mathbf{Hp} - \mathbf{Cv} = \mathbf{p}_{\mathrm{p}} \tag{4}$$

where $\mathbf{H}$ and $\mathbf{C}$ are boundary element influence matrices, and $\mathbf{p}$, $\mathbf{v}$ are vectors of the acoustic pressure and normal velocity at nodal points of the structure.

To overcome the time consuming simulation run times and data storage requirements to solve a 3D model of an infinitely long barrier, a quasi-periodic BEM technique is developed as follows. The surface of the barrier is divided into identical sections Γ_n, where *N* and *M* are the number of sections in the positive and negative directions along the length of the barrier from the centre boundary section Γ_0. Hence, the boundary of the barrier Γ can be represented as follows

$$\Gamma = \Gamma_{-M} \cup \Gamma_{-M+1} \cup \cdots \cup \Gamma_{-1} \cup \Gamma_0 \cup \Gamma_1 \cup \cdots \cup \Gamma_n \cup \cdots \cup \Gamma_{N-1} \cup \Gamma_N \tag{5}$$

The total length of the boundary is equal to $L_T = (N + M + 1)x_p$ where x_p is the length of one periodic section. For the quasi-periodic barrier, it is not necessary to discretise the entire surface of the domain, since the nodal coordinates of the centre section can be used for the entire structure. Hence, Eq. (4) can be rewritten as a sum over the sectionwise nodal acoustic pressures and particle velocities as follows

$$\sum_{n=-M}^{N} \mathbf{H}_n\mathbf{p} - \sum_{n=-M}^{N} \mathbf{C}_n\mathbf{v} = \mathbf{p}_{\mathrm{p}} \tag{6}$$

$\mathbf{H}_n$ and $\mathbf{C}_n$ are the sectionwise boundary element matrices and $\mathbf{H}_0$ contains the coefficients $c(\mathbf{x})$.

Sound attenuation by a noise barrier is presented in terms of insertion loss using the following expression [12]

$$IL \;= 20\log_{10}\left|\frac{P_g}{P_b}\right| \tag{7}$$

where P_g and P_b are the acoustic pressure at the same receiver position without and with the presence of the barrier, respectively.

3. Results and Discussion

3.1 Barrier geometry

A quasi-periodic rectangular barrier with a thickness of 0.5 m and a height of 3 m is initially modelled. An equal number of periodic sections corresponding to M=N=400 were used on each side of the centre section. The length of each quasi-periodic section is 1 m, resulting in a total barrier length of 801 m. Two configurations of the barrier were developed corresponding to with and without embedded Helmholtz resonators. Each quasi-periodic barrier section was discretised using linear discontinuous boundary elements. A higher mesh resolution was used near the Helmholtz resonators.

Figure 1 shows the configuration of a single periodic barrier section with and without a Helmholtz resonator. Ten monopole sources are associated with each periodic barrier section, where the monopole sources are located at a height of 0.01 m above the ground and at a normal distance of 1 m from the mid-plane of each periodic section. The receiver is located on the ground in the shadow zone of the barrier. Figure 2 presents a schematic diagram of one periodic section of the noise barrier showing the location of point sources.

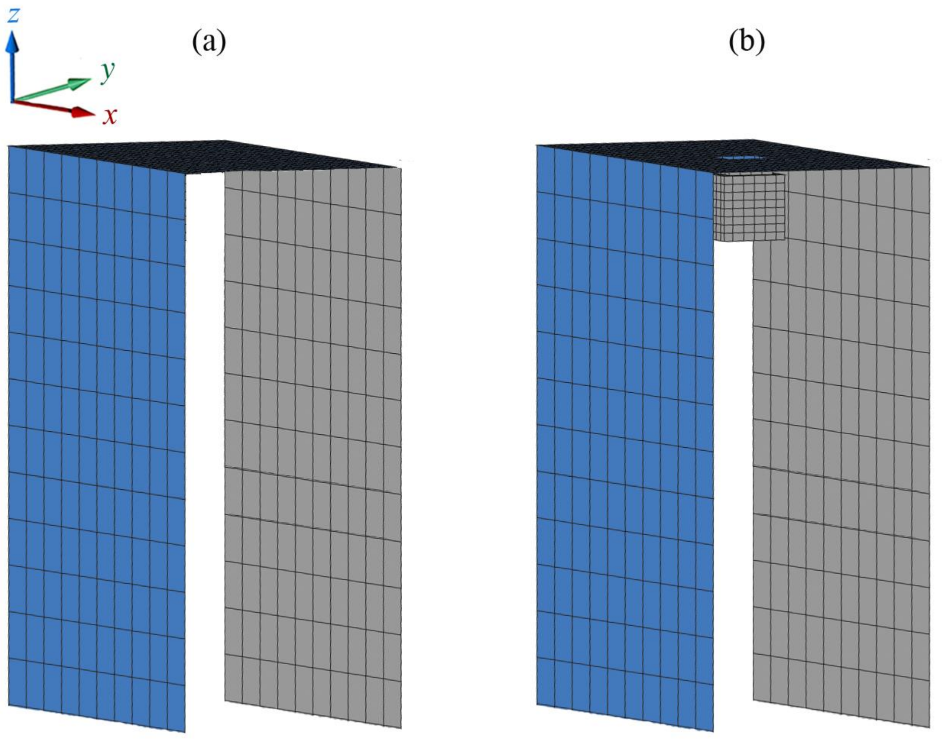


Figure 1. A quasi-periodic barrier section without (a) and with (b) a Helmholtz resonator

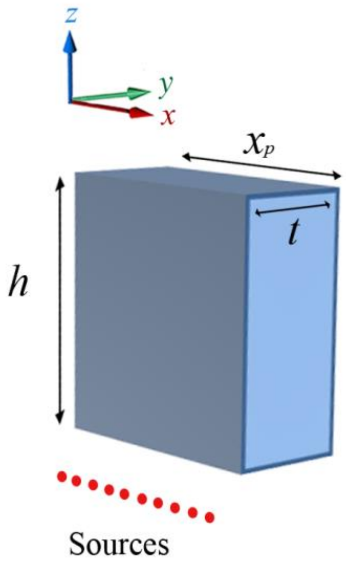


Figure 2. Configuration of a single periodic barrier section showing the point sources

3.2 Helmholtz resonators tuned to a single frequency

Figure 3 presents the insertion loss for the quasi-periodic barrier design in the absence of an embedded Helmholtz resonator (Figure 1a) and with a single Helmholtz resonator embedded along the top surface of each periodic section (Figure 1b), where each Helmholtz resonator is tuned to the same single frequency. Helmholtz resonators tuned to resonant frequencies of 200 Hz and 250 Hz are considered. For these models, the receiver is located 5 m from the mid-plane of the quasi-periodic barrier. The presence of Helmholtz resonators embedded along the top edge of the barrier tuned to resonant frequencies of 200 Hz or 250 Hz results in an increase in insertion loss at frequencies above the target frequency. However the acoustic performance of the barrier at frequencies just below the target frequency is slightly deteriorated.

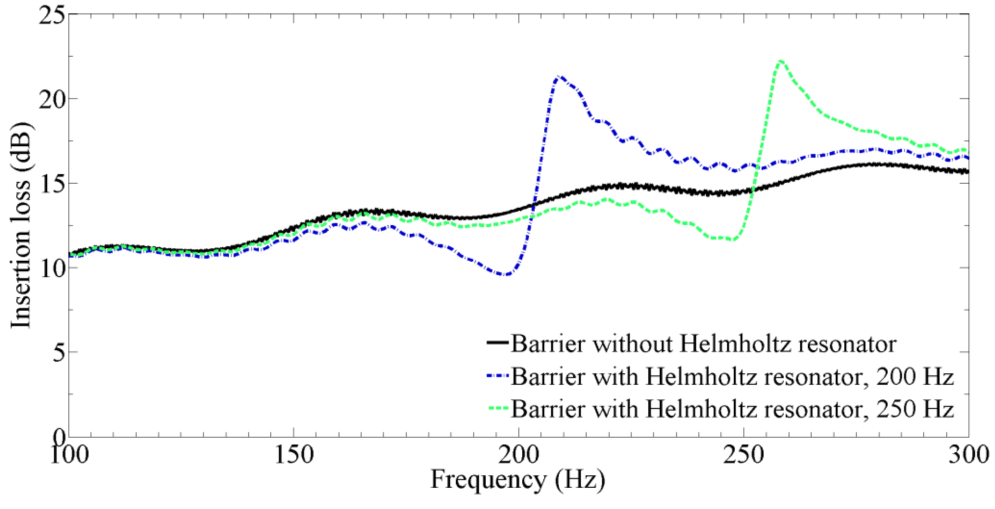
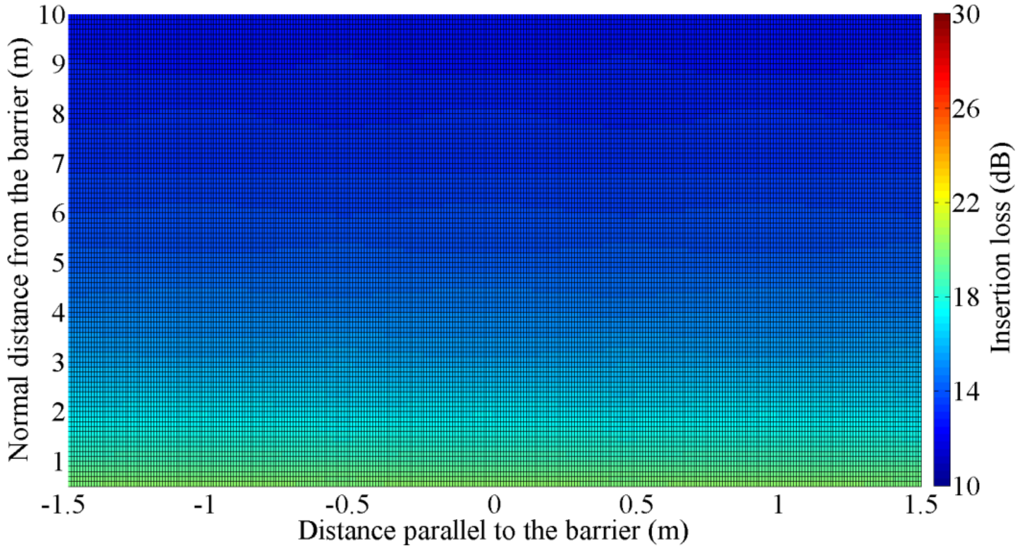
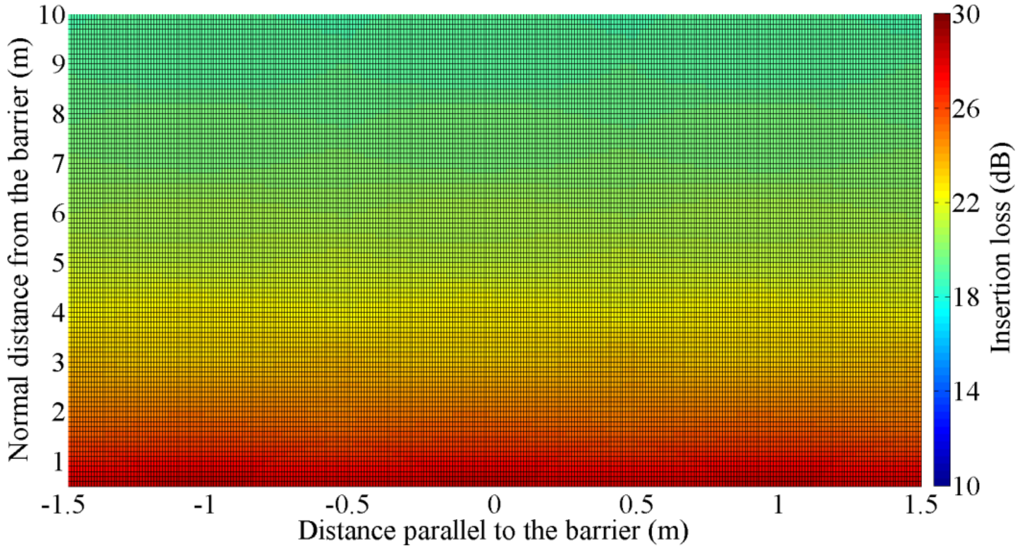


Figure 3. Insertion loss of quasi-periodic barrier without and with a Helmholtz resonator tuned to resonant frequency of 200 and 250 Hz

The acoustic performance of the quasi-periodic noise barrier model with and without a Helmholtz resonator tuned to a resonant frequency of 200 Hz was examined in the shadow zone of the barrier for a range of receiver positions. Normal to the barrier, the shadow zone extends to a distance of 10 m from the barrier. Parallel to the barrier, the receivers are located from -1.5 m to 1.5 m. The insertion loss in the shadow zone of the barrier is presented in Figure 4 at 210 Hz, at which the peak insertion loss in Figure 3 occurs. There is a gradual reduction in insertion loss for both models with increasing normal distance from the barrier. In Figure 4(a) which corresponds to the straight barrier without Helmholtz resonators, attenuation of at least 12 dB can be observed in the entire shadow zone. For a barrier with embedded Helmholtz resonators, significantly greater insertion loss of at least 20 dB is achieved as shown in Figure 4(b).



(a)



(b)

Figure 4. Insertion loss at 210 Hz in the shadow zone of a quasi-periodic barrier (a) without and (b) with embedded Helmholtz resonators tuned to a frequency of 200 Hz

6. Summary

In this work, the effect of Helmholtz resonators on the acoustic performance of a rectangular noise barrier was explored using a quasi-periodic BEM technique. The quasi-periodic BEM technique predicts the insertion loss for the entire rectangular barrier by modelling only the centre periodic section of the barrier. One Helmholtz resonator tuned to a low frequency was incorporated into each periodic section of the barrier. Higher noise reduction was achieved for the barrier with embedded Helmholtz resonators for a frequency range above the tuned frequency. Future work will investigate the use of multiple Helmholtz resonators in each periodic section tuned to different frequencies to achieve greater performance over a broadband frequency range.

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