Low-frequency noise reduction by a noise barrier made of a resonator array

Jieun Yang[1,a], Maarten Hornikx[1,b]

[1] Department of the Built Environment, Eindhoven University of Technology,
P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[a] j.yang3@tue.nl, [b] m.c.j.hornikx@tue.nl

Abstract
Noise barriers reduce the level of noise that reaches the receiver by interrupting the noise propagation path. Even though noise barriers are effective at high frequencies, low-frequency control remains challenging as sound waves at low frequencies are easily diffracted over the barriers. In this work, we show that by designing noise barriers designed with an array of tuned resonators can achieve high attenuation, more than 5 dB, of noise at low frequencies. The propagation of low-frequency waves is significantly suppressed by the interplay of the tuned resonators installed on the surface of the noise barriers. Analytical models and numerical simulations are used to calculate the insertion loss by the designed noise barriers.

Keywords: noise barrier, insertion loss, noise control, periodic resonators.

1 Introduction

Controlling low-frequency sound waves is challenging due to their long wavelengths in comparison to the geometrical dimensions of the acoustical systems that can be installed. In the case of noise barriers, low-frequency waves diffract around the noise barrier easily. Hence, the sound attenuation performance of noise barriers in the low-frequency range is relatively poor. To improve the performance of noise barriers, several methodologies in designing noise barriers have been proposed including a tilted barrier [1], the addition of an edge on the top [2,3], and the use of techniques to optimize its geometry [4,5]. More recently, the application of sonic crystals [6,7] and acoustic metamaterials [8,9] to noise barriers has been explored. These works have shown that insertion loss at certain frequency ranges can be improved by sound attenuation effects due to the Bragg gap induced by periodicity or due to localized resonances occurring at the used resonators. However, the presented works so far solely focused on the influence of the periodicity along the wave propagation path in between the source and the receiver. The heights of the structures were considered infinite, therefore, the influence of wave diffraction at the top of the barrier was not investigated with the exemption of a few studies [7].

In this work, we aim to show that the diffracted wave around the barrier can be utilized to enhance the attenuation performance of the noise barrier at low frequencies. Unlike the previous works using sonic crystals [6,7], the resonators are periodically arranged along the direction perpendicular to the ground, in other words, the resonators are placed along the surface of the noise barrier. It will be shown that by using these periodic resonators, sound attenuation will increase not only at the resonator's resonance frequency but also in the frequency range below resonance. We will use theoretical analysis to demonstrate that the proposed configuration excites guided wave modes confined at the surface of the noise barriers. In turn these modes increase sound attenuation at certain frequencies. Numerical simulations based on the finite element method will be used to illustrate the underlying physical mechanism. The insertion loss generated by the proposed noise barrier will be numerically computed and compared with the insertion loss of a nominal barrier.

2 Insertion loss by the noise barrier with periodic resonators

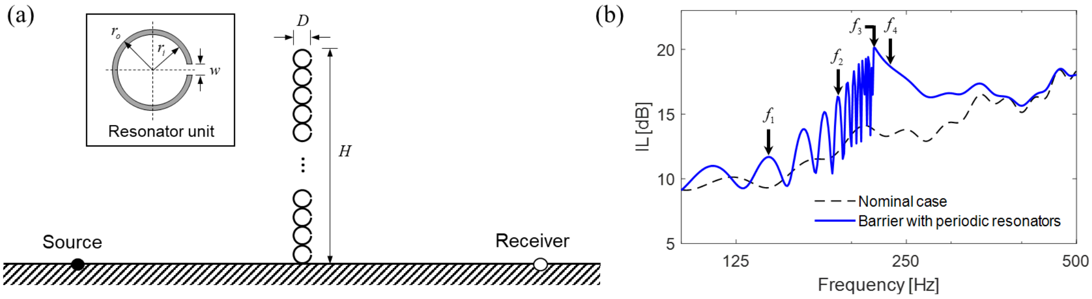

Figure 1 – (a) Geometric configuration of the noise barrier comprised of periodic resonators. A zoomed view of the resonator unit is shown in the black-lined box. (b) Insertion loss by the barrier with periodic resonators (blue line) compared with the one by a nominal noise barrier (black dashed line).

Figure 1(a) shows the configuration of the noise barrier considered in this work. The noise barrier is placed between the sound source and the receiver. The barrier consists of 20 Helmholtz resonators of split-ring shape. The resonators are attached to form a monolayer along the vertical direction. A detailed geometry of the split-ring resonator unit is presented in the black-lined box in Fig. 1(a). The diameter (D=2r_o) of the resonators is 0.20 m, which makes the total height of the barrier (H) 4.0 m. The inner radius of the ring (r_i) is 0.09 m and the opening width of the slit (w) is 0.02 m.

To evaluate the noise reduction performance of the barrier, numerical simulations based on the finite element method using COMSOL Multiphysics® [10] were conducted. A monopole source was placed 6.0 m away from the left-hand side of the barrier as shown in Fig. 1(a). The ground was assumed to be acoustically rigid. To simulate an unbounded domain, a perfectly matched layer (PML) was placed around the air domain. Figure 1(b) presents the insertion loss of the noise barrier in the frequency range of 100-500 Hz calculated at a receiver placed 6.0 m away from the right-hand side of the barrier. The insertion loss of the nominal barrier, which has the same dimensions as the proposed barrier with closed cylinders, is also presented. The graph shows that the attenuation is significantly increased when using a periodic array of resonators as opposed to the nominal case. The highest peak occurs at 220 Hz, which corresponds to the resonance frequency of the split ring resonator. In addition, the insertion loss of the barrier with periodic resonators shows multiple peaks in frequencies below 220 Hz as well as a wideband increase of the insertion loss above 220 Hz.

3 Wave behaviour around the noise barrier

To clarify the physical mechanism of the observed increase in insertion loss in Fig. 1(b), the wave behaviour around the noise barrier with periodic resonators is examined. Before discussing the effect of the periodic resonators, we need to explain wave behaviour around the nominal barrier. When sound waves encounter discontinuities in the propagating medium, a diffraction phenomenon occurs. In the case of the noise barrier, waves behave as if there is a secondary sound source emitting sound at the top of the barrier. These diffracted waves interfere with waves that are reflected from the ground surface. This interference of diffracted and reflected waves forms harmonic standing wave patterns along the barrier in the vertical direction. At frequencies where the top of the noise barrier becomes an antinode, the insertion loss slightly increases and vice versa, which results in the small peaks and troughs observed in Fig. 1(b) in the black-dashed line (nominal case).

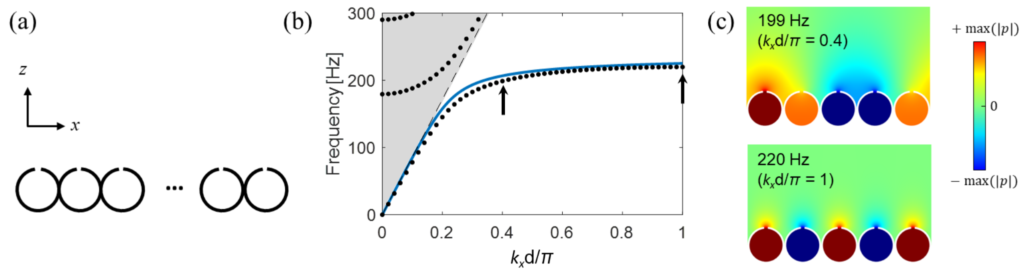

Figure 2 – (a) Split-ring resonators are periodically arranged along the x-direction. (b) Dispersion curve of the acoustic waves propagating along the x-direction above the periodic split-ring resonators. (c) Acoustic pressure distribution at 199 Hz (top) and 220 Hz (bottom).

The periodic resonators change the propagation characteristic of the sound waves along the noise barrier. Previously it was reported that when a sound wave propagates along a horizontal periodic structure comprised of a resonator unit, a guided mode is generated on the surface [11,12]. When the size of the resonator unit is small compared to the wavelength of the sound waves, the dispersion relation of this guided mode can be derived by using the effective medium theory. We consider a periodic monolayer of split-ring resonators shown in Fig. 2(a). By considering the interaction of the waves propagating above the structures and the resonator units, the dispersion relation can be derived as,

$$\sqrt{k_x^2 - (\omega/c_0)^2}\,(\omega_0^2 - \omega^2) = \omega^2 \frac{\phi A}{m}, \tag{1}$$

where k_x is the x component of the wavenumber, ω is the angular frequency, c_0 is the speed of sound in air, ω_0 is the resonance frequency of the split ring resonator, ϕ is the average fraction area of the neck, A is the area of the opening, and m is the acoustic mass of the resonator.

Figure 2(b) shows the dispersion curve of the periodic structure. The blue line indicates results obtained by using Eq. (1) and the black dots are the results obtained by numerical simulation. The straight dashed line indicates the sound line, i.e., dispersion of the bulk wave in the air. For small values of k_x, the dispersion of the guided mode follows that of the sound line, but when k_x increases, the frequency converges to the resonance frequency of the resonator. Figure 2(c) shows the mode shapes (sound pressure distribution) of the guided mode at frequencies of 199 Hz and 220 Hz, respectively (the corresponding points on the dispersion curve are indicated by the black arrows in Fig. 2(b)). The mode shapes display that the sound fields are confined near the surface of the monolayer of periodic resonators. In such guided modes, the wave velocity becomes slower and the group velocity eventually reaches 0 when the frequency approaches the resonance frequency of the resonator. In other words, the waves propagate with a velocity slower than the speed of sound in air for frequencies below the resonance frequency, and the waves are eventually trapped when approaching the resonance frequency.

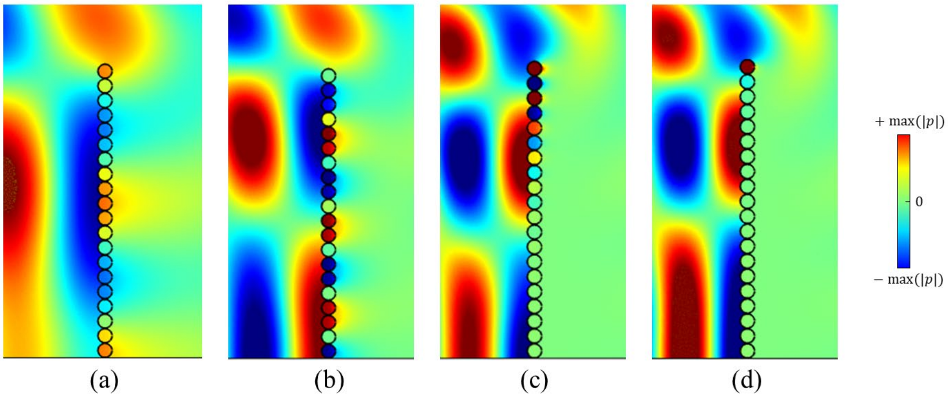

Figure 3 – Acoustic pressure fields around the noise barrier with periodic resonators at frequencies (a) f_1, (b) f_2, (c) f_3, and (d) f_4 denoted in Fig. 1(b).

Figure 3 shows the acoustic pressure fields around the noise barrier at selected frequencies. Figures 3(a) and 3(b) show the pressure fields at f_1 and f_2, respectively, indicated in Fig. 1(b). Note that these frequencies are below the resonance frequency. From the pressure fields presented in Figs. 3(a) and 3(b) we see that the waves show the pattern of the guided mode confined at the surface of the resonators, as was explained earlier. Another noticeable thing is that these wave patterns are the ones of standing wave patterns along with the height of the noise barrier, which indicates that the multiple peaks below the resonance frequency (220 Hz) are due to combined effects of the guided mode generated by the nature of the periodic resonators and the standing wave modes around the noise barrier. As explained with Fig. 2(b), the waves below the resonance frequency are slowed down compared to the bulk wave in air. Due to the effect of this slow sound, the frequencies that correspond to such standing wave modes move to lower frequencies.

Figures 3(c) and 3(d) show the results at f_3 and f_4 denoted in Fig. 1(b), which corresponds to the resonance frequency and a given frequency above the resonance frequency, respectively. Unlike the standing wave patterns shown in Figs. 3(a) and 3(b), the pressure distribution at and above the resonance frequency shows wave behaviours that appear in the resonance gap of the sonic crystals. In this resonance gap, sound energies are highly concentrated in the first few unit cells along the direction of the wave propagation and do not transmit any further. Especially in Fig 3(d), it is observed that the waves interact only with the first resonator located at the top of the noise barrier. As the sound energies are localized at the resonators, the sound energy transmitted through the noise barrier can be significantly reduced. It should be noted that the physical origins of the sound attenuation at the frequencies below (Figs. 3(a) and (b)) and above the resonance frequency (Figs. 3(c) and (d)) show distinctive behaviours. The waves below the resonance are propagating guided modes along with the periodicity of the structure, whereas the waves above the resonance have evanescent nature.

4 Conclusions

In summary, we showed that a vertical array of periodically arranged resonators can be used to improve low-frequency performance of a noise barrier. Theoretical analysis showed that the sound waves diffracted at the top of the barrier turn into guided waves confined along the surface of the noise barrier below the resonance frequency of the resonator unit. The wave propagation velocities of the guided waves are much slower than that of the bulk wave in air. Numerical simulations presented that guided waves that interact with reflected waves from the ground surface form harmonic standing wave patterns along the surface of the barrier. It has been shown that sound attenuation can be increased at frequencies corresponding to these standing modes assisted by guided waves. Around the resonance frequency, wave propagation behaviour around the noise barrier can be described as what happens in a band gap induced by localized resonance. An increase in the insertion loss in this band gap was also observed. This research demonstrates that vertical periodic structures can be used to control diffracted waves around the noise barrier and be designed in such a way that they reduce low-frequency noise transmission. Future work may include further tuning the resonator unit to desired specifications, adding top edges (e.g., T- or Y-profiles), and investigating the influence of ground impedance and meteorological conditions.

Acknowledgments

This research was supported by funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 754462.

References

[1] May, D.N.; Osman, M.M. Highway noise barriers: new shapes, *Journal of Sound Vibration*, 71, 1980, 73-101.

[2] Okubo, T.; Fujiwara, K. Efficiency of a noise barrier with an acoustically soft cylindrical edge for practical use, *The Journal of the Acoustical Society of America*, 105(6), 1999, 3326-3335.

[3] Oldham, D.J.; Egan, C.A. A parametric investigation of the performance of T-profiled highway noise barriers and the identification of a potential predictive approach, *Applied Acoustics*, 72(11), 2011, 803-813.

[4] Grubeša, S.; Jambrošićm, K.; Domitrović, H. Noise barriers with varying cross-section optimized by genetic algorithms, *Applied Acoustics*, 73(11), 2012, 1129-1137.

[5] Kim, K.; Yoon, G. Optimal rigid and porous material distributions for noise barrier by acoustic topology optimization, *Journal of Sound and Vibration*, 339, 2015, 123-142.

[6] Sánchez-Pérez, J. V.; Rubio, C.; Martinez-Sala, R.; Sanchez-Grandia, R.; Gomez, V. Acoustic barriers based on periodic arrays of scatterers, *Applied Physics Letters*, 81(27), 2002, 5240-5242.

[7] Castiñeira-Ibáñez, S.; Rubio, C.; Sánchez-Pérez, J. V. Acoustic wave diffraction at the upper edge of a two-dimensional periodic array of finite rigid cylinders. A comprehensive design model of periodicity-based devices, *Europhysics Letters*, 101(6), 2013, 64002.

[8] Lee, T.; Nomura, T.; Dede, E. M.; Iizuka, H. Ultrasparse Acoustic Absorbers Enabling Fluid Flow and Visible-Light Controls, *Physical Review Applied*, 11(2), 2019, 024022.

[9] Wu, H.-W.; Yin, Y.-Q.; Sheng, Z.-Q.; Li, Y.; Qi, D.-X.; Peng, R.-W. Multiband omnidirectional ventilated acoustic barriers based on localized acoustic rainbow trapping, *Physical Review Applied*, 15(5), 2021, 054033.

[10] COMSOL Multiphysics® v. 5.4. www.comsol.com. COSOL AB, Stockholm, Sweden.

[11] Zhu, J.; Chen, Y.; Zhu, X.; Garcia-Vidal, F. J.; Yin, X.; Zhang, W.; Zhang, X. Acoustic rainbow trapping, *Scientific Reports*, 3, 2014, 1728.

[12] Maznev, A.; Gu, G.; Sun, S.; Xu, J.; Shen, Y.; Fang, N.; Zhang, S. Extraordinary focusing of sound above a soda can array without time reversal, *New Journal of Physics*, 17(4), 2015, 042001.