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Sound Barrier Model with Sonic Crystal Structure for Attenuating Noise Due to Road Transportation Activity

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Abstract: Transportation activities are a source of noise in the urban environment. The urgency of reducing noise caused by transportation in residential areas has led to the development of new sound barrier models. In this study, we present a novel sound barrier model with a sonic crystal structure for attenuating noise due to road transportation activity. The sonic crystal structure used in this study comprised a PVC tube with a diameter of 16.5 cm (6 inches) and a height of 4 meters. The measurement of noise attenuation was conducted by carrying out a full-scale experiment with a square lattice-critical sonic model. The proposed model was based on a combination of experimental and numerical approaches, using finite element analysis in ANSYS. The experimental study was conducted to measure the maximum noise reduction and insertion loss in the frequency range of 12.5 to 20,000 Hz. The results show a maximum noise reduction of 20.98 dB and an insertion loss of 2.5 dB (A), indicating the effectiveness of the proposed sound barrier model. A numerical simulation using finite element analysis in ANSYS was performed to investigate the sound attenuation behavior of the sonic crystal structure with respect to different frequency ranges. The simulation results show that the proposed model effectively attenuated high-frequency sound waves in the range of 1000 to 8000 Hz. The results suggest that the proposed sound barrier model with a sonic crystal structure could be an effective solution for reducing transportation noise in residential areas, and further research could explore the application of the model in other noise pollution scenarios.

Keywords: acoustic barrier; environmental solutions; noise reduction; traffic noise control

1. Introduction

Exposure to noise pollution is becoming increasingly prevalent in modern society, with sources including traffic, industrial machinery, construction sites, and airplanes. The World Health Organization (WHO) estimates that around 1.1 billion people worldwide are at risk of hearing loss due to exposure to noise pollution. In addition to hearing loss, excessive noise exposure has been linked to a variety of physical and mental health problems, including cardiovascular disease, sleep disturbances, cognitive impairment, and increased stress levels. The negative health effects of noise pollution are not limited to humans. Research has shown that wildlife is also impacted by noise pollution, with noise exposure altering the behavior, physiology, and even reproductive success of many species. For example, noise pollution from shipping traffic has been linked to changes in whale behavior and vocalization, which can impact their ability to communicate and find food[1–3]. One of the most prevalent contributors to environmental stress and discomfort in daily life is transportation noise, which is mainly caused by road vehicles, trains, and airplanes[4]. Aircraft noise during take-off can reach 140 dB, and noise from traffic conditions on urban roads during the day can reach more than 80 dB. The lowest noise limit is 55 dB and the highest is 70 dB[5]. Noise is generated by mobile and static sources. Mobile sources produce movable or immovable emissions originating from motorized vehicles, and static sources are fixed in one place[6].

Noise can be detrimental because it endangers human health and affects environmental comfort[7]. In its 2018 Environmental Noise Guidelines for the European Region[8], the WHO claimed that high-quality data are available to prove that traffic noise increases the risk of ischemic heart disease. People's quality of life is negatively impacted by noise, which is a major source of environmental disturbance. Moreover, while they may be minor, the effects on health and cognition may also be substantial due to the growing number of people exposed to environmental noise and the chronic nature of this exposure[9]. Research by Carter showed that years of chronic exposure to traffic noise during sleep may negatively affect heart rate and mood states[10-11]. Research by Lan et al. showed that transportation noise has a significant impact on anxiety levels[12]. These studies highlight the significance of noise reduction to enhance the health of the population.

Two common noise-reduction techniques are noise isolation and noise absorption[13]. Isolation techniques reduce noise by disrupting and blocking sound transmission, whereas absorption techniques reduce noise by absorbing and weakening sound energy. Exposure to traffic noise can be reduced by applying mitigation techniques to the sources of noise, such as upgrading vehicle engines and minimizing tire/road emissions by utilizing certain surfaces[14]. The use of noise barriers is the most popular method of reducing the vulnerability of those affected, despite the fact that such solutions are not always feasible, affordable, or even adequate[15]. The presence of noise barriers can decrease outdoor and indoor noise disturbances up to 100 meters from the main road[16]. The spectral absorption behavior of conventional barriers is virtually homogeneous across the A-weighted normalized traffic emission spectrum, which is typically between 100 Hz and 5 kHz, with a peak centered at 1 kHz[17]. However, the presence of a wall causes issues such as sound reflection from one side of the wall to the other, visual obstruction, and obstructed air circulation[15].

Sonic crystals represent a novel solution to noise pollution issues. Sonic crystals are artificial structures formed by periodic scattering in a square, rectangular, or triangular configuration[18]. To reduce noise impact, the authors of[19] modeled rows of Thuja trees planted systematically along the edge of a road. The results indicated that trees could be used to reduce traffic noise, because there was significant sound attenuation within the 500 Hz frequency range. This finding is consistent with the findings from research demonstrating that arranged trees can be used to reduce traffic noise[20], as well as air pollution and vibrations[21]. In addition, a noise barrier system utilizing sonic crystals, called a sonic crystal acoustics screen, which exhibited a remarkable acoustic response, was proposed in[22].

Sonic crystals are periodic structures used to attenuate mechanical waves with audible frequencies[23]. Sonic crystals were first used in 1995 in the form of a periodic circular sculpture exposed to sound waves. Although the scatterers on the sculpture were not in their perfect form, a significant percentage of transmission loss was demonstrated throughout the open area[24]. Sonic crystals have the particular characteristic of selective sound attenuation in a specific frequency range due to their periodic arrangement of scatterers[18]. It was found that sound transmission is significantly decreased in this frequency range, which is known as the band gap region[25]. The destructive interference of waves in the band gap causes such sound attenuation.

Several distinct properties influence sound transmission loss and the location of band gaps in sonic crystals: the form of periodic arrangement, the filling fraction, and the interspacing lattice constant play crucial roles in the design of sonic crystals. Ad-justing the interspacing lattice constant can alter the band gap's central frequency. In addition, the filling fraction and periodic arrangement can induce expansion and fractioning of the band gap[26,27]. Sonic crystals are widely used for sound insulation. The characteristics of a one-dimensional sonic crystal were demonstrated via a multilayer partition based on periodic layer arrangement. This one-dimensional sonic crystal effectively reduced the transmission frequency[28]. Sonic crystals have also been effectively used as frequency filters, acoustic waveguides, sound diffusers, acoustic diodes, and liquid sensors[18].

One approach to mitigating transportation noise is the use of sound barriers. However, conventional sound barriers have a limitation in terms of their effectiveness in attenuating noise across a wide range of frequencies. To overcome this limitation, in this study, we propose a sound barrier model with a sonic crystal structure that is designed to attenuate noise across a broader frequency range. We aim to contribute to the development of effective transportation noise-reduction strategies for residential areas. The proposed model shows promising results in attenuating noise across a broad fre-quency range, and further research could explore the application of the model in other noise pollution scenarios.

This work investigated the effectiveness of a crystal sonic structure as a traffic noise barrier. Large-scale studies of noise attenuation are rare, so it is anticipated that this novel experimental study will contribute to noise attenuation research. In this study, we constructed a full-scale model of a square lattice of PVC sonic crystals and measured its sound absorption performance. To determine the capability of sonic crystals to absorb incident sound, several distance points were determined to measure the attenuation of sound pressure. This value could be further used for reference in policy making regarding the distance from transportation noise sources to sonic crystals when measuring noise attenuation levels. The proposed sound barrier model is based on a com-bination of experimental and numerical approaches using finite element analysis in ANSYS software. The experimental study was conducted to measure the maximum noise reduction and insertion loss of the proposed model in the frequency range 12.5 to 20,000 Hz. The numerical simulation using finite element analysis in ANSYS software was performed to investigate the sound attenuation behavior of the sonic crystal structure with different frequency ranges.

2. Current Situation in Indonesia

Currently, the most common method used to mitigate transportation noise in Indonesia is to block the sound propagation path with noise reduction barriers. The manufacture and implementation of noise-reduction barriers are regulated in Keputusan Direktur Jenderal Bina Marga related to the Pedoman Perencanaan Teknik Bangunan Peredam Bising No. 036/T/Bm/1999 and the Pedoman Konstruksi dan Bangunan, Pd-T-16-2005-B, related to the mitigation of noise impacts due to road traffic. There are three forms for noise-reduction structures according to Bina Marga: standard, curved, and roofed. According to the Construction and Building Guidelines, Pd-T-16-2005-B, noise barriers can be either natural or artificial. Natural barriers usually use various combinations of plants with pile soil, while artificial barriers can be made using wood, precast concrete panels, aerated lightweight concrete, fiber cement panels, transparent acrylic panels, or steel.

2.1 Concrete

Concrete and red brick are the most practical materials for in-the-field noise-reduction structures. In addition to their practicality, these materials make the structures easier to design and maintain. However, they have drawbacks, including poor aesthetic value. To improve the aesthetic properties, concrete combined with bricks and river stones can be used for noise barriers, as shown in Fig. 1.

Fig. 1: Noise-reduction structures made from concrete: (a) concrete, brick, and river stone; (b) concrete and brick.

2.2 Acrylic and Plexiglass

Acrylic and plexiglass are transparent materials that can be used in noise-reduction structures. The typical thickness of acrylic is 3–8 mm, while plexiglass has a thickness of 15–20 mm[29]. Noise reduction structures that are made from acrylic or plexiglass are generally curved or semi-circular. As a result, the material can improve the building's aesthetic appeal. The drawback of these materials is that they are prone to damage, particularly in the event of vandalism.

2.3 Metal (Lightweight Steel)

Metal is a versatile material that is easy to color and shape. The metal used to reduce noise typically has a thickness of 1–2 mm[29]. The metals used are those that are resistant to corrosion, such as mild steel, aluminum, stainless steel, and other readily available materials. Metal noise-reduction structures can be combined with sound-absorbing materials. For instance, soundproofing materials can be applied to metal that has been perforated or combined with vegetation. An example of using metal materials for noise barriers can be found in the Jakarta–Bandung high-speed railway project in Indonesia, shown in Fig. 2. It is claimed that the plate material that was installed with the concrete composite in that structure can reduce noise up to 30 dB(A). Plate installation with this combination is expensive, and implementation in the field is complicated because it requires special orders.

Fig. 2: Composite noise-reduction structure made from metal plate and concrete for Jakarta–Bandung high-speed railway project, Indonesia.

2.4 Green Open Space

Sodiq et al. [30] conducted research on controlling noise due to aviation activities in the environment around an airport by utilizing green open space. Using green open space as a natural barrier should be accompanied by planting vegetation. Natural noise barriers consist of plants that grow from the top to the bottom. An evaluation of 2.3 hectares of green open space showed that its use as a natural barrier to reduce noise is considered less effective because it is only able to reduce noise by 2.11 dB.

2.5 Vegetation

Research on the efficacy of noise absorption by different varieties of trees along roads in Gorontalo Province was carried out by Hamidun et al.[31]. Trees are known to create a pollution-free environment because they absorb pollutant gases, lower the temperature, and absorb sound through their trunks, branches, and leaves. The presence of vegetation can reduce noise by 8.6 dB(A), and the density of leaves and branches can absorb and block sound, with sound absorption of about 0.6%[32]. Trees are limited in their ability to absorb sounds that are too loud, in contrast to other types of barriers such as walls, which have higher absorption levels. This is because groups of trees do not provide an absolute barrier, but have an open arrangement, so there are still gaps for sound waves to pass through. Sound absorption will be most effective if trees have good crown density and minimal gaps. In residential areas, the use of vegetation is usually combined with brick walls. The use of vegetation, in addition to reducing noise, increases the aesthetic value of the structure, as shown in Fig. 3.

Fig. 3: Vegetation combined with brick walls as noise barriers: (a) bamboo; (b) vines.

2.6 Wood

In research conducted by Hidayat et al. (2020), camphor wood (Dryobalanops sp.) was used as a sound barrier material[33]. Sound barriers made with camphor wood have added value in terms of aesthetics and because it is an environmentally friendly material. Based on the quality of the wood, camphor wood is classified as durable class I–III; the class is determined by the length of use in conditions affected by the weather but not submersion in water and not lacking air, and can be 10–20 years. Economically, it is cheaper and more efficient to use camphor wood as a sound barrier material than acrylic. However, in terms of its ability to absorb noise, camphor wood is less effective because it is a thin and light material. The heavier and thicker the material or layer of material, the better the damping ability, not only because it suppresses resonance, but also because it is better able to absorb sound waves entering through its pores.

3. Material and methods

3.1 Materials

This study was carried out using a sonic crystal arrangement, which was like those used in indoor experiments by Morandi et al. and Sánchez-Pérez et al. [34,35]. The sonic crystal was made of PVC with a diameter of 6 inches and a height of 4 m; the experiment was performed outdoors at full scale. The width of the sonic crystal lattice is 3 m, and the distance between each sonic crystal, measured from the center, is 20 cm. The distance value was adopted from research by Morandi et al.[34]. The selection of 4-meter-tall sonic crystals was based on the possibility of sound sources being located at or below the 4-meter level, considering that the height of motorized vehicles ranges between 1.3 and 4.1 meters[36]. Thus, it is likely that microphones (in residences, hospitals, schools, and offices) will be situated below the sound source. In this investigation, we combined data from[34,35], which utilized the same width and thickness. Microphones were placed 1 m apart in front of and behind the sonic crystals, while a sound source was positioned 5 m in front of the sonic crystals. The variance of the microphones is given in Table 1. Before impacting the sonic crystals, the sound produced by the sound source was captured by the front receiver. The back receiver recorded the sound that traveled through the sonic crystals. Fig. 4 shows the configuration of the sonic crystals.

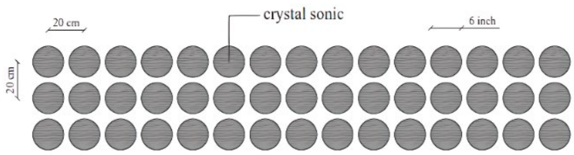


Fig. 4: Sonic crystal configuration

3.2 Experimental setup

Noise measurement was carried out using a sound level meter in open areas with noise levels that could potentially disturb community settlements. The sound source and receivers were placed in the locations shown in Fig. 5, which were used to make a sound intensity distribution contour map.

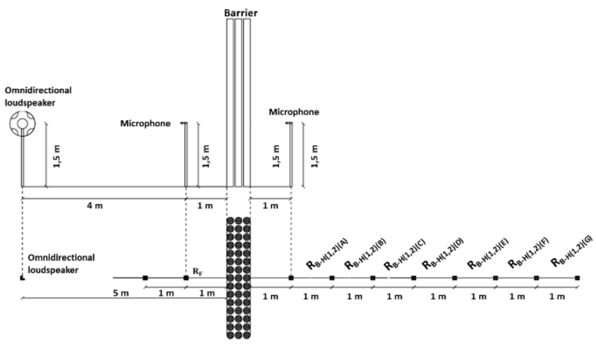


Fig. 5: Experiment configuration

For the experimental work in this study, the equipment included a sound level meter, amplifier, omnidirectional speaker, and microphone. A Type 2270 sound level meter (Brüel & Kjaer, Denmark) was employed to measure sound pressure levels. It consists of a microphone, preamplifier, main processor, and reading unit. The microphone converts the sound signal to an electrical signal equivalent. The OmniPower Type 4292-L is used for acoustic measurement and requires sound radiation to spread in all directions with a constant magnitude. The OmniPower is compliant with ISO 3382, ISO 140, and DIN 52210 standards and is commonly used in outdoor and indoor acoustics applications. The Type 4190 half-inch free-field microphone was specifically designed for high-sensitivity free-field measurements. This microphone was connected via an extension cable to the sound level meter. Finally, a Type 27341 power amplifier was employed to generate the sound during outdoor and indoor acoustic measurements; it has a built-in generator capable of providing sound frequencies in the 50–5000 Hz range. The device setup for data measurement is shown in Fig. 6.

Fig. 6: Device setup for data measurement

During the analysis, the sound absorbed by the sonic crystals was determined. The sound level meter recorded the intensity level of sound before and after passing through the sonic crystal. At each test point, the frequency spectrum (Hz) that produced sound (dB(A)) was analyzed using the Surfer application. The receiver recordings before and after the sound crystal barrier were compared to determine the amount of sound absorption affected by the square-lattice sonic crystals. The data obtained were processed using Surfer, an open-source application (Golden Software) to create sound distribution contours. The mapping results that were processed with Surfer were then compared with the mapping results obtained through the numerical approach using ANSYS software.

A previous study explored the effect of building facades on transportation noise interference[37] using a frequency spectrum of 100 Hz to 5 kHz, with transportation noise from a 6-lane highway as the sound source, where the speed of a car was about 80 km/hour, and 15% came from heavy vehicles. Frequencies of 100–5000 Hz due to the sound of transportation activities were also reported in[35], in which the EN 1993:1997 standards were adopted. Based on those studies, the data analysis in this study also used frequencies in the range 100 Hz to 5 kHz.

According to Indonesian National Standard RSNI T-14-2004, the minimum height of a passenger vehicle is 1.3 meters. The most widely used small city cars in Indonesia are the Honda Brio, with a height of 1485 mm, the Toyota

Agya, with a height of 1520 mm, and the Daihatsu Ayla, with a height of 1520 mm. Based on these dimensions, in this study we adjusted the microphone height to 1.5 m at the sound source points. The receivers were arranged at 1.5 m and 2.0 m for the microphones, considering the average human height. The receivers were placed at 1–8 m behind the sonic crystals. Information on the receivers is shown in Table 1.

Table 1. Details of receivers.

Position Relative to Sonic Crystals	Level of Microphone (m)	Distance from Sonic Crystals (m)	Code
Front	1.5	1	R_F
Behind	1.5	1	$R_{B-H1 (A)}$
Behind	1.5	2	$R_{B-H1 (B)}$
Behind	1.5	3	$R_{B-H1 (C)}$
Behind	1.5	4	$R_{B-H1 (D)}$
Behind	1.5	5	$R_{B-H1 (E)}$
Behind	1.5	6	$R_{B-H1 (F)}$
Behind	1.5	7	$R_{B-H1 (G)}$
Behind	1.5	8	$R_{B-H1 (H)}$
Behind	2.0	1	$R_{B-H2 (A)}$
Behind	2.0	2	$R_{B-H2 (B)}$
Behind	2.0	3	$R_{B-H2 (C)}$
Behind	2.0	4	$R_{B-H2 (D)}$
Behind	1.5	5	$R_{B-H2 (E)}$
Behind	1.5	6	$R_{B-H2 (F)}$
Behind	1.5	7	$R_{B-H2 (G)}$
Behind	1.5	8	$R_{B-H2 (H)}$

3.3 Numerical modeling and simulation setup

The finite element method (FEM) is a process by which an object is divided into small pieces to obtain an analytical solution. FEM is an approximate mathematic approach for solving engineering problems. Many problems, such as stress analysis, heat transfer, fluid flow, and electric fields, have been solved using the finite element method. The concept involves dividing geometric shapes into multiple elements to calculate multiple displacement values at nodes (node points) to obtain a solution. In general, finite element analysis (FEA) uses three types of analysis: 1D modeling, which is used to solve beam, rod, and frame elements; 2D modeling, which is useful for solving field stress and plane–strain problems; and 3D modeling, which is useful for solving complex solid structures.

In modern engineering, FEA software such as ANSYS has been extensively applied for rapid analysis. The steps for problem-solving in ANSYS are as follows. First, in the pre-processing phase, a model is defined based on the geometric arrangement, materials, and element shapes, which are divided into nodal and elemental forms, and mathematical equations are constructed based on the boundary conditions. Second, in the solution phase, the mathematical equations in the previous stage are solved based on predetermined boundary conditions. Finally, in the post-processing phase, the results of the equations are displayed in the form of legend colors, curves, and the vector direction of forces. Finite element methods for noise barriers have been reported using software such as ANSYS.

Cylindrically spreading acoustic waves in a fluid medium can be expressed using Equation (1):

$$\nabla^2\rho + k_o^2\rho = 0 \qquad (1)$$

where $\nabla^2 = \frac{\partial^2}{\partial_{x_1}{}^2} + \frac{\partial^2}{\partial_{x_2}{}^2}$ is the Laplacian, $k_o = \frac{2\pi f}{cD}$ is the wave number in air, and the complex-valued function ρ satisfies the well-known Helmholtz equation in unbounded space occupied by air. The expressions for the pressure emitted by either a plane wave or a cylindrical source are, respectively, given by Equations (2) and (3):

$$p_{in\_p} = e^{ik^0x}, \qquad (2)$$

$$p_{in\_p} = \frac{i}{4}(J_0(k_0r_c)-iY_0(k_0r_c)) \qquad (3)$$

where $r_c = \sqrt{x_c^2 + y_c^2}$ is the distance defined by the source location to the traveling wave position. The direction of waves is normal to the symmetry axis of the scatterer.

An acoustically hard boundary condition (widely known as the Neumann bound-ary condition) is defined to model the rigid surface of the scatterers, in which the normal acceleration of the particle velocity is equal to zero, as expressed by Equation (4):

$$\vec{n}.\left(\frac{1}{\rho_0}\nabla p\right) = 0 \qquad (4)$$

where ρ_0 represents the density of the scatterer. Computing two-dimensional scattering problems in an unbounded domain involves domain decomposition by introducing an artificial boundary around the obstacles. The radiation boundary conditions are applied to the surrounding boundaries of the modeling domain. For an outward traveling wave, this boundary condition ensures minimal or no reflections from the model boundary. The radiation boundary conditions can be expressed by Equation (5):

$$-\vec{n}\left(-\frac{1}{\rho_0}\nabla p\right)+\left(ik_0 + k(r)\frac{p}{\rho_0}\right) = \left(ik_0 + k(r) - i(\vec{K}.\vec{n})\right)\frac{p_0}{\rho_0}e^{-i(\vec{k}.r)} \qquad (5)$$

where k(r) is a function whose form depends on the type of wave, as described by Equations (6) and (7):

$$\text{plane wave: } k(r) = 0, \text{ or} \qquad (6)$$

$$\text{cylindrical wave: } k(r) = \frac{1}{2r} \qquad (7)$$

where r is defined as the shortest distance from the point

(8)

on the boundary to the source. The insertion loss (IL) for the sonic crystal noise barrier can then be obtained using Equation (8):

$$IL = 20\log_{10}\left|\frac{p_{direct}}{p_{total\ transmitted}}\right|$$

The finite element method starts with meshing. Meshing is a process that breaks a three-dimensional object into thousands of cells to provide a precise definition of the physical shape of the object. In this study, a tetrahedral element was used in the meshing setup with a size of 250 mm at the enclosure, and a total of 230,375 elements were obtained. Figure 7 shows the meshing process. The parameters involved in determining the mesh quality include aspect ratio, orthogonal quality, and skewness. Table 2 shows the mesh parameters for the model.

Table 2. Mesh parameters.

Parameter	Value
Skewness	0.263
Aspect ratio	2.016
Orthogonal quality	0.735

The analysis setting is achieved by performing a frequency sweep across 12.5 Hz to 20 kHz with a solution interval of 20. The acoustic region is set at the enclosure of the barrier. The radiation boundary is set at the face of the enclosure, with a total of 6 faces, and the mass source is set at the location of the loudspeaker, with a magnitude of $2.32 \times 10^{-3}\ \frac{kg}{m^2 s}$.

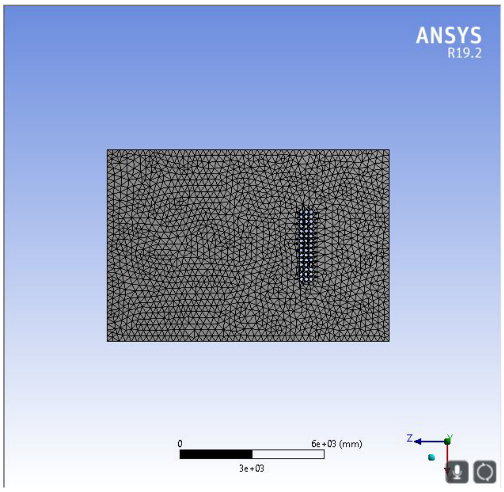


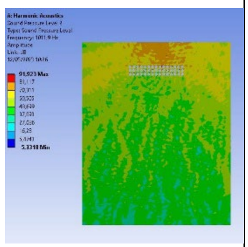
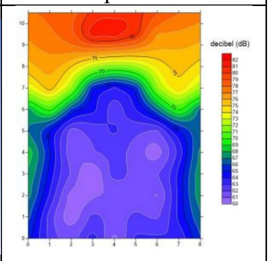
Fig. 7: Meshing for setup simulation.

4. Results and discussion

4.1 Sonic crystal performance

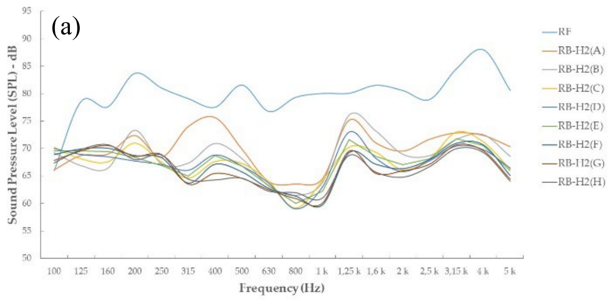
To determine the accuracy of the sound distribution map in the field, a sound distribution contour was drawn. Not all frequencies are displayed in this contour. Table 3 shows the comparison of FEM-predicted and experimental sound pressure levels at a frequency of 1000 Hz with a level 1 microphone. This involved a visual examination to determine the effectiveness of sonic crystals. The results obtained are almost the same as the contour results at a frequency of 1000 Hz between FEM and the experiment.

Table 3. Sound distribution results between FEM and experiment at 1000 Hz with level 1 microphone.

Height	Sound Distribution Contour	
	FEM	Experiment
1.5 m		

Figures 8 and 9 show the magnitude of the sound pressure and insertion loss after the sonic crystals absorbed the noise at the frequencies of highway transportation activities (100–5000 Hz) for the back receiver at a height of 1.5 m (RB1) and 2.0 m (RB2) and 1 to 8 m from the sonic crystals. The average RF noise level was 80.09 dB(A). Both figures show that noise reduction occurred at all frequencies. At a frequency of 100 Hz, a tendency for noise increments is apparent, which shows a negative value in noise reduction. This also occurred in another study[35], which showed an increase in noise after passing through sonic crystals at a sound source at a frequency of 100 Hz.

Figure 8 shows that receiver point 1 (RB-H1) had higher average noise reduction at a further distance from the sonic crystals, with values ranging from 9.95 to 13.97 dB(A) at distances from 1 to 8 meters. The standard deviation of noise reduction at each observation distance for RB-H1 ranges between 4.95 and 6.08 dB(A). The maximum noise reduction at each observation point was 17.8–20.98 dB(A). The maximum reduction occurred at 1000 Hz. This finding agrees with[15], in which the A-weighted normalized traffic emission spectrum, typically between 100 Hz and 5 kHz, was reported to have a peak centered around 1 kHz.



(b)

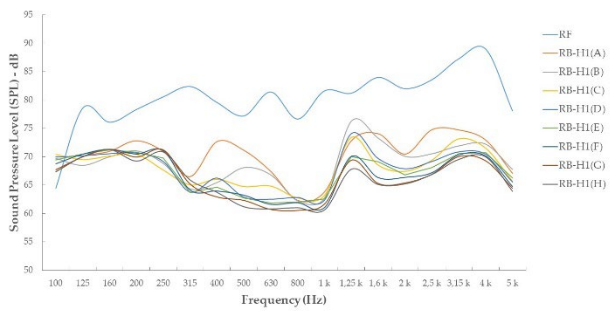


Fig. 8: Sound pressure level at (a) receiver RBH-1 at 1.5 m and (b) receiver RBH-2 at 2.0 m.

The amounts of noise reduction at 1 to 8 m by the sonic crystal structure at RBH-1 and RBH-2 were 12.42–17.44% and 12.68–17.30%, respectively. The significance test (t-test) of the difference in average noise in RBH-1 and RBH-2 shows no significant difference in sound reduction at 1.5 and 2.0 m with a sound source at the same height. The significance test for average noise obtained a value of $p = 0.116 > 0.05$. A negligible difference was also found in the magnitude of the noise decrease at 1.5 and 2.0 m, with a sound source at the same height. The significance test of noise reduction obtained a value of $p = 0.840 > 0.05$.

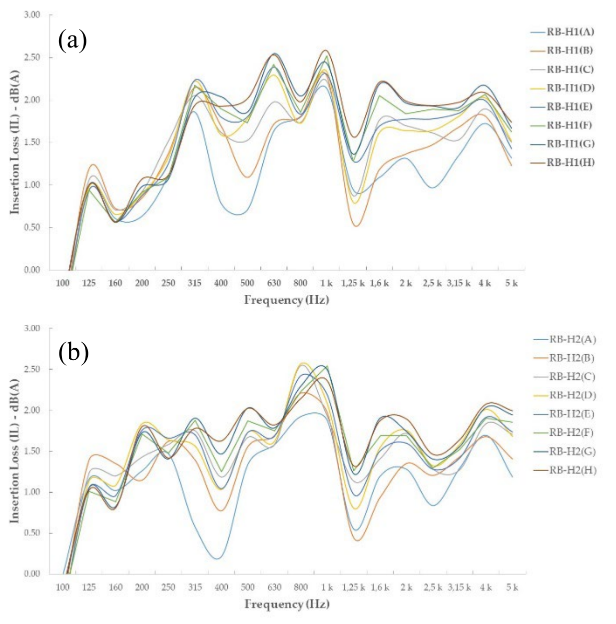


Fig. 9: Insertion loss at (a) receiver RBH-1 at 1.5 m and (b) receiver RBH-2 at 2.0 m.

2. Manuscript format

Insertion loss describes the reduction in signal strength or power caused by the insertion of components or devices in the signal path. It is expressed in decibels (dB) and is usually measured relative to the input signal level. Higher insertion loss indicates greater signal attenuation, which can affect system performance. As can be seen in Fig. 9, insertion loss was highest at a frequency of 1000 Hz, which means that the signal strength was most severely attenuated at that frequency. The magnitude of this attenuation was 2.5 dB(A), which represents the amount of signal power lost or ab-sorbed as the signal passed through the system.

The unit of measurement in this case was dB(A), which includes a weighting factor that is adjusted according to the sensitivity of the human ear to different frequencies. This weighting was based on A-weighted filters, which are commonly used to measure sound levels in environmental noise assessments. Overall, insertion loss is an important parameter that must be considered when designing or evaluating signal paths in various applications, including telecommunications, audio systems, and power distribution networks. By measuring and minimizing insertion loss, the overall performance and reliability of the system can be improved.

4.2 Discussion

The results of studies of a sonic crystal structure in the laboratory, utilizing a three-line square model structure with dimensions of 3 m × 3 m[29)], showed a decrease of up to 24 dB(A) at the reception point behind the structure. Another study[35)] examined a sonic crystal acoustic screen (SCAS) design using a triangular lattice with dimensions of 4 m × 3 m, and showed insertion loss capability of up to 20 dB(A). A wind tunnel test[2)] revealed a 42% reduction in overturning momentum compared to conventional noise barriers. Laboratory experiments in a wind tunnel have been conducted to estimate the values of wind blowing in an SCAS compared with a classical acoustical barrier formed by a wall.

Using 2D boundary element method (BEM) numerical simulations, low-height sonic crystal noise barriers with enhanced resonance and absorption qualities were introduced in metropolitan areas as an effective method to reduce traffic noise[38)]. For road traffic and tramway noise, a sonic crystal barrier built of solid resonance cylinders showed global insertion losses of 9.5 dB(A) and 9.0 dB(A). Those values increased to 11.9 dB(A) and 13.9 dB when the interior of the cylinders was lined with an absorbent sub-stance. Sound attenuation by a waveguide can be directly determined by simulating a finite sonic crystal as a waveguide and calculating the sound transmission through the waveguide using Webster's horn equation. Webster's horn equation shows considerable sound attenuation (>20 dB(A)) for a finite sonic crystal[39)]. In[14)], the authors compared insertion loss (IL) data from various sources. In the development of sonic crystal structures with various materials, it was shown that the maximum insertion loss (IL) of polyvinyl chloride (PVC) was 20 dB(A) at a frequency of 1 kHz. At the same frequency, IL could reach 30 dB(A) with aluminum cylinder material.

Experimental techniques have been used with Helmholtz resonators to study sonic crystals[40)]. Due to its straightforward structure and reliable noise absorption capabilities, the Helmholtz resonator is one of the most frequently applied devices for passive control of low-frequency noise over a narrow band[40]. An array of sonic crystals was used in three distinct environmental conditions throughout the study: indoor, semi-indoor, and outdoor. IL values at 1000 Hz for tests conducted indoors and outside were 3.64 and 9.85 dB(A), respectively. For indoor and semi-indoor tests, sonic crystal attenuated 4.24 and 4.50 dB(A) of noise, respectively, at 2000 and 6300 Hz. The sonic crystals achieved the highest reduction in outdoor testing, around 11.81 dB(A) at 800 Hz[40].

The insertion loss of traffic noise barriers, including interlocking steel panels, precast concrete panels, and Paragon panel 23-T, was examined using data collected by[41]. That study demonstrated that the insertion loss of all three types of noise barriers was in the range 7.02 to 13.58 dB(A) under the given circumstances, which was influenced by other key parameters. Research using acoustic topology optimization (ATO) for the design of noise barriers with rigid and porous materials at 2–8 m from the sound source at ground level[42] revealed a decrease in the sound pressure level (SPL) by approximately 4 dB(A). Experiments were conducted on barriers made of porous materials in various forms (y-shaped, cylindrical, and T-shaped), and on T-shaped barriers with diffuse quadratic residuals.

In this study, an outdoor sonic crystal structure experiment was conducted, which demonstrated noise reduction of up to 20.98 dB(A). The structure's insertion loss of up to 20 dB(A) is in accordance with the results of lab tests in other experiments[32,33]. Regarding material use, the maximum IL of PVC cylinders was 20 dB(A) at a frequency of 1 kHz in[15], as was observed in this study. The use of PVC sonic crystals as noise absorbers in this study resulted in higher insertion loss compared to other tested noise barrier materials[39,40]. This finding supports the potential of applying sonic crystal structures as noise dampers for highways.

Based on the findings of previous studies, the level of traffic noise in Indonesia is high, given that the noise limits are 55 dB(A) for residential areas and 60 dB(A) for public facilities[5]. The average noise level measured 5 meters from the edge of a collector road (Monginsidi Street) in Surakarta City is approximately 79.78 dB(A), with the lowest and highest noise levels measuring 77.72 and 82.08 dB(A), respectively[43]. According to one study[44], the noise level on the secondary arterial road (Ir. Juanda Street) ranges from 75 to 90 dB(A) during the day. Similarly, the noise level of Soekarno-Hatta Street in Semarang City during daytime activities can reach 90 dB(A)[45]. According to D20), Sam Ratulangi Street in Manado City has the highest noise level at 81.89 decibels. Moreover, the average noise level at Uluwatu II Street in Denpasar at a distance of 5 meters from the road is 73.23 dB(A)[46].

According to 45), in 1999, the minimum height and wall thickness of a noise-canceling structure were 2.75 m and 10 cm, respectively. Materials that can be used as noise-canceling materials are artificial low weight aggregate (ALWA) block material, red brick, or batako. The guidelines also state that the minimum placement of the structures should be 5 m from arterial roads or 10 m from toll roads. With limited land available and a rapidly increasing population, it will be difficult to adhere to the minimum distance of noise-canceling structures.

In 2005, the Indonesian government developed guidelines for mitigating the impact of traffic noise. The manual covers handling noise at sound sources[2], noise propagation paths, and noise receiving points. Noise control can be accomplished by regulating traffic, limiting heavy vehicles, controlling speed, improving road inclination, and selecting the appropriate road pavement.

Limiting the volume of vehicles in the form of traffic engineering, such as constructing ring roads, can reduce the noise level by about 2–5 dB(A). Restricting heavy vehicles by 10% can reduce noise by approximately 3.5 decibels. Controlling speed in the range 30-60 km/h can reduce noise by about 1-5 dB(A). Reducing the slope by every 1% can reduce the noise level by 0.3 dB(A). According to 2), at speeds exceeding 80 km/h, the noise correction on different types of pavements can reach -3.5 to -4.0 dB(A).

By installing noise-canceling structures, noise control is accomplished by sound propagation. A noise-canceling structure is constructed in the form of a barrier in the sound propagation path using specific shapes and materials to reduce noise levels caused by automobile traffic. The principle of a noise-canceling structure is that it provides sound insulation, absorption, and diffraction. The barrier wall provides reflection, absorption is provided by the wall-forming material, and diffraction is provided by the upper end of the barrier. The noise level that reaches the receiver is a combination of the residual sound absorption level and the result of diffraction. The effectiveness of a noise barrier is determined by the insertion loss (IL), an indicator of the level of noise reduction. IL is the value of the difference between the noise level received with and without a barrier[2].

Noise barriers are available in both natural and artificial forms. Natural barriers are usually composed of various combinations of plants with soil berms, whereas artificial barriers can be made of various materials. Bricks, reinforced concrete, wood, aluminum, steel, fiber, and glass are some of the noise barrier materials mentioned in[2], and combinations of several of these materials are possible. A noise-canceling structure with a width of 0.3–2.0 meters and a height of 2.0–4.0 meters can effectively reach an IL of up to 22 dB(A).

One of Indonesia's noise reduction attempts is the installation of noise barriers made of artificial low weight aggregate (ALWA) blocks. A 2.75-meter-high noise barrier built along Uluwatu II Street, Jimbaran, at 5 meters from the edge of the pavement was investigated. The noise level without the noise barrier was 73.23 dB(A); with the noise barrier, it was 61.85 dB(A)[46], indicating an insertion loss of 11.38 dB(A). Research on the effectiveness of using plants as noise absorbers was carried out on several major roads in Gorontalo Province[47,48], and a maximum sound absorption of 16 dB(A) was reported.

The guidelines for mitigating the impact of traffic noise that are applied in Indonesia still use the conventional form, which is a structure with a vertical shape. This shape is thick, so it is not economically efficient. The use of sonic crystals is an option for reducing the impact of transportation-related noise. The benefits of sonic crystals include their light weight, ease of disassembly, ability to be made from waste materials such as plastic, and aesthetic potential.

5. Conclusions

This research was conducted using a sound barrier model with a sonic crystal structure that can effectively attenuate noise caused by road transportation activity. The experimental results show a maximum noise reduction of 20.98 dB and insertion loss of 2.5 dB(A), indicating that the sound barrier was successful in reducing the amount of noise that passed through it. The contour maps generated from the experimental and numerical simulations also support the effectiveness of the sound barrier model in at-tenuating noise. This suggests that the use of sonic crystal structures may be a viable solution for mitigating noise pollution in communities located near busy roads, and that sonic crystals have the potential to produce more effective noise-reduction structures than the existing noise barrier materials. The results also highlight how important it is for regulations in Indonesia related to noise reduction on roads to consider the potential of sonic crystals in noise-reduction structures. Policymakers and urban planners should consider the use of sonic crystals as a viable option for noise reduction in the built environment. Finally, our conclusions emphasize that further research is needed on the application of sonic crystals in the field. This means that, while laboratory experiments have shown promising results, more research is needed to assess the effectiveness of sonic crystals in real-world settings and to develop practical guidelines for their implementation.

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