Comparative analysis of the acoustic efficiency of classical and sonic crystal noise barriers

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Abstract. This study presents a comparative analysis of the acoustic efficiency of classical and sonic crystal noise barriers conducted by means of numerical simulation. One of the most common solutions for transport noise reduction is the use of expensive combined noise barriers of high degree of reflection and absorption. Sonic Crystals are a relatively new type of noise barrier under development and investigation. In this study both types of barriers are compared on the basis of their area of application, noise level attenuation behind them, frequency response, technology of manufacturing, maintenance and price. Some of the characteristics are obtained through numerical simulations and experimental data, while others are available in published research studies. On the basis of the results conclusions about the application of sonic crystal noise barriers are made.

1. Introduction
The comfort of the urban areas is one of the most important tasks to achieve when we talk about noise and environmental contamination. That is the reason why in recent years, many researchers have focused their attention on the construction and optimization of acoustic barriers. More than 55 dBA in the night hours and 65 dBA in the day hours should not be exceeded according to EU normative, however a large number of European citizens suffer higher noise levels. In fact, 20% of EU citizens during the day, and the 30% of citizens during the night suffer higher noise levels. The most commonly used method for sound insulation is the installation of acoustic screens between the noise source (transport infrastructure) and the receiver (the near urban areas). These classical Acoustic Barriers (AB) are made of continuous flat walls whose main noise control mechanism is reflection. However, some unwanted problems may arise due to this reflected noise energy and even cause a noise increase at protected areas, reducing the effectiveness of the installed ABs. To minimize these specular reflections, some solutions have been developed, such as the use of absorbent materials, the installation of inclined barriers, or scattering of the reflected noise [1-3]. However, the application of absorbent materials can be very expensive, and the use of inclined barriers could be technically complicated and impossible in some sites. Focusing on the solution of scattering the reflected noise, some proposals have been presented recently. One of the most widely accepted solutions is the use of new noise control devices based on technologically advanced materials. Sonic Crystals (SC) is one of these materials. SC are generally defined as heterogeneous materials formed by arrangements of acoustic scatterers embedded in air. Two of the many applications of these materials are their use as Acoustic Barriers (ABs) usually called Sonic Acoustic Screens (SCAS), and their use as sound diffusers in acoustic rooms to increase sound diffuseness [1-3].

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1.1. Barrier types
All noise barriers should be designed in order to meet the requirements of the local environment; otherwise they can remain dull, only visual elements who damage the landscape quality. The visual quality of the barriers is also an important issue, which should be carefully considered, and this effect depends on the barrier height, the distance of the barrier from the receiver, etc.

Depending on the acoustic and non-acoustic requirements and the terrain configuration, the process of noise barrier selection should be carefully done. In figure 1 different types of noise barriers are presented.

![Different types of acoustic barriers](image)

**Figure 1.** Different types of acoustic barriers [4].

Depending on the physical dimensions of the barrier and the location, an appropriate barrier material should be chosen. The materials can be divided into five groups, as follows:

- **Timber acoustic materials:** may be fully reflective or sound absorptive. Depending on the application the structure may be composed of absorbing materials covered with timber elements with a tongue and groove constructions (for sound absorptive elements, for example), or the timber elements can be jointed in order to avoid leaks (for reflective barrier, for example).
- **Metal acoustic elements:** the metal materials used here are mostly aluminium, steel or both and the construction is typically cartridge-type panels. Such barriers could be sound reflective or sound absorptive.
- **Concrete acoustic elements:** usually used for the structural part of the precast panels in concrete, and covered by porous concrete (cement or wood-fibre type).
- **Transparent acoustic elements:** they are commonly used for visual impact for the people, offer a view of the road for the drivers. They can be fully transparent or incorporated as part of a barrier constructed from other materials.
- **Plastic or composite acoustic elements:** usually the panels are made from plastic, which is reinforced with glass fibre. They can be sound reflective and absorptive. In order to be absorptive the front part of the panel should be perforated.

There are a lot of bad examples of barriers. The problems are various and can be manifested due to problems with materials, for example. Rust is the main problem for metallic barriers. Their structure-caissons are suitable for water from the rain to remain in it and this humidity may develop inside. Typical problems for timber barriers are warping, shrinkage and crocking. Over time the transparency of the transparent barriers diminishes and the main characteristic of the device is lost.

Innovative noise barriers solutions can be considered that use more innovative design or materials for construction of the acoustic elements, or perform some additional functions, such as power generation as addition to noise mitigation. Some examples for innovative sound isolation barriers with their advantages and disadvantages are described below.

- **Combined noise and safety barriers:** use both concrete and steel guardrails and serve as a safety barrier and an acoustic barrier, ensuring double advantage – to recover the mounted width and optimized bearing construction. One advantage of such barriers is that they can be
placed closer to the noise source and thus protection increases significantly. Some of them are free-standing and do not need foundation for their construction. The main disadvantage is that the maximum tested height of such barriers is 5 meters with metal guardrail and 4 meters with concrete safety barriers.

- Photovoltaic noise barriers: they are used as combination of noise reduction and production of renewable energy, converting sound energy into electricity. The advantage here is that it limits the production of greenhouse gas emissions in the atmosphere. The photovoltaic panels can be directly integrated into the surface of the barrier or mounted onto the barrier. The advantages are environmental, economic and social. The disadvantages are related to the fact that they are not suitable for every situation because they are dependent upon the orientation of the barrier, the number of photovoltaic cells and the climate (the sunlight) and the energy use. The cost benefits should be carefully considered against the cost of the energy storage and transfer infrastructure.

- Noise barriers with TiO2 coating: such type barriers incorporate TiO2 coatings and thus employ photo catalysis, which is a chemical reaction where titanium oxide acts as a catalyst to eliminate nitrogen oxides. These type of barriers have limited effectiveness and success in practical trials.

- Inox/corten steel barriers: they are made of stainless steel or corten steel and have a lot of performance requirements. Their advantages include good environment insertion, positive perception by the population, mechanical strength and stability, ease of maintenance, easy removal of dirt and graffiti. The main disadvantage of these barriers is the cost.

- Sonic crystals: the sound attenuation characteristics could be tuned by appropriate selection of the lattice constant and cylinder radius. The height of these barriers can reach 6 m [4].

1.2. Sonic crystal basics
The first possibility, presented as an alternative to the classic acoustic screens, is the use of sound crystals (SCs). The basic unit of the ideal crystal structure can be defined as an identical group of atoms (in terms of composition, arrangement and orientation) in space (see figure 2).

![Figure 2. An ideal crystal structure](image)

SCs can be defined as a heterogeneous material consisting of a periodical array of acoustic diffusers embedded in an environment of different physical properties, where one of the materials is a liquid. Depending on the number of directions where the array periodicity exists, one dimensional (1D), two-dimensional (2D), and three-dimensional (3D) SC crystals (figure 3) can be defined.

1.3. Sound crystal acoustic screen (SCAS). Main characteristics of the sound crystals
The mechanism that prohibits the transmission of sound through the system is different from those prevailing in the classical acoustic screens (AS), in that case the main physical mechanism is the destructive Bregg Interference due to the Multiple Scattering (MS) process associated with the periodicity of system. These destructive disturbances lead to damping peaks. These peaks expand by increasing both the number and the diameter of the cylinders so that these periodic systems show ranges of frequencies associated with the periodicity of the structure where there is no wave propagation. These frequency ranges are called Band Gaps. Other physical mechanisms such as absorption or reflection can be added to the dividers to enhance damping capabilities.
Figure 3. Schematic illustrations of crystal structure (a) one-dimensional, (b) two-dimensional and (c) three-dimensional [7-8].

By using group theory, it has been proven that there is only one unique 1D periodic system, five 2D and 14 different 3D grids. Most of the studies are focused on the sound crystal as a 2D arrangement for which the five different Bravais grids with their principal lattice vectors and angles are shown in figure 4.

Figure 4. The five fundamental 2-Dimensional Bravais lattices (a) square, (b) oblique, (c) rectangular, (d) centered rectangular and (e) hexagonal [6].

The sound crystals/Sonic crystals (SC) are non-homogeneous materials made from regular arrays of separators embedded in a liquid or air environment. An interesting feature of these materials is the occurrence of ranges of frequencies in which periodic structures are not supported. These ranges are known as band gaps (BG). The center frequency of the fBG bandwidth is determined by the grid constant α which represents the distance between adjacent diffusers:

\[ f_{BG} = \frac{c}{2\alpha} \]  

where c is the speed of the sound in the air.

Over the last two decades, an increasing number of studies and applications have been presented that analyze the distribution of acoustic waves inside sound crystals. Solid spacers, such as wood or aluminum, are used to study the physical behavior of sound crystals when the reflection of acoustic waves becomes a mechanism for creating bandwidth. In addition, sound crystals with mixed solid and absorbent materials are used to study the double reflection and absorption effect on the frequency response of the acoustic crystal. In fact, the use of soft cylinders is an alternative to solving the problem of angularity of acoustic attenuation. Resonance cylinders allow the sound to penetrate the elements of the periodic structure and as a result new acoustic properties may emerge. In fact, in urban areas, pedestrians and cyclists are in close proximity to road traffic or noise sources from urban...
transport. It is easy to protect with small devices not exceeding $1 \times 1$ m in vertical section. Engineering methods cannot produce accurate values for the acoustic damping of such barriers [7-8].

1.4. First and second generation sonic crystals

Acoustic screens of sonic crystals have developed various solutions such as the use of absorbent materials, the construction and installation of bending barriers or noise distraction that is reflected. The application of absorbent materials may be expensive and the installation of bending barriers is difficult and complicated. That is why most research aims to scatter the reflected noise and develop new materials such as sonic crystal.

The first experimental barrier for sound isolation by a periodic structure is in the form of a sculpture (made in 1995) in Madrid and consists of periodically spaced hollow cylinders. Their material is stainless steel and has a diameter of 0.029 meters. They are located in a constant grid and the distances between the cylinders are the same - 0.1 m (see figure 5). These cylinders are the sonic crystal, they can rotate around a vertical axis. The sound isolation is measured under different conditions. The acoustic barriers based on SC are usually called Sonic Crystals Acoustic Screens (SCAS) [9].

The first generation of SCAS are new noise reduction devices that use a new noise control mechanism based on the presence of a bandgap (see figure 6). These new barriers have some technological advantages over the classical acoustic barriers but also have a deficiency in noise coverage.

![Figure 5. Minimalistic sculpture by Eusebio Sempere [9].](image)

![Figure 6. Sound attenuation as a function of frequency, also known as Insertion Loss [9].](image)

In order to improve the SCAS characteristics and noise control capabilities, other solutions were proposed in 2011 by Romero-García. The design uses resonances or absorption mechanisms. A core of rigid cylinders with a slot along the entire length and a wrap of absorbent material are formed. The interior becomes an acoustic resonator cavity. The outer part with absorbent material contributes to noise suppression. Resonator cavities have damping peaks due to resonances. There are three mechanisms for noise control: band gap, absorption and resonance.

SCASs that use other noise control mechanisms, with the exception of band gap, are called second-generation SCASs [10].
Figure 7. (a) Example of first generation SCAS; (b) Simulated attenuation spectrum of the SCAS [10].

Figure 7(a) shows an example of first generation SCAS and figure 7(b) shows the characteristics of the second generation SCAS. The peaks attenuation can be seen due to resonant cavity 1, whose position in the frequency range depends on the volume of the resonators. The damping peaks due to the periodicity of the array correspond to the band gap of the array 3, 4. The attenuation threshold due to the absorption used in each cylinder of the construction occurs from 500 Hz onwards [10].

This new generation of acoustic barriers allows for the design of specific acoustic screens to reduce noise. This design of the second-generation SCAS is protected by Spanish patents (Sánchez-Pérez et al., 2003). Comparative analysis of standard acoustic barriers and sonic crystals is made and detailed in the next section.

2. Comparison between classical acoustic absorber and sonic crystal barrier

2.1. Sonic Crystals and classical acoustic barrier

The modern way of life makes it easier for us in every respect, but at the same time there are negative sides - we are subject to pollution. A very common source of pollution is noise, which has reached alarming levels and leads to stress and a number of ailments in people who are exposed to it for a long time. Dealing with this problem is the subject of activity of many companies.

Noise in the physical sense is a sound with a complex inharmonious wave (chaotically collected tones), whose frequency and strength are not in definite and constant proportions in time; in the psycho-physiological sense - any acoustic irritation (impact), which is perceived as unpleasant, regardless of its acoustic qualities; in the patho-physiological sense - any acoustic signal that causes with its strength or duration temporary or permanent changes in the body (auditory analyzer and beyond).

The classical acoustic barriers (figure 8a) are strong and solid barriers between the highway and the houses that are located along this highway. They do not completely block the noise, but only reduce it by 5 to 10 decibels (dB), limiting noise traffic by almost half. Barriers can be made from earth embankments along the road, from high, vertical panels of different materials (wood, metal, acrylic glass, recycled plastic, etc.) or from a combination of earth embankments and panels. Earth embankments look most natural and are therefore attractive to contractors and are common. They reduce noise by about 3 dB more than vertical walls of the same height but making them requires a large amount of soil, especially if they have to be taller.

Barriers, on the other hand, take up much less space, but their height is usually limited (up to 8 m) due to structural and aesthetic reasons. The barrier reduces the noise that reaches the settlement from the busy highway by absorbing, transmitting and reflecting it back to the road or directing it along a long path above and around the barrier. The noise barrier must be high and long enough to "block" the road from the highway to the area to be protected - the "receiver". It should be noted, however, that it brings minimal benefits to houses on slopes that are higher than the highway or buildings that rise above the barrier.
The noise barrier can reduce noise by up to 5 dB when it is high enough to break the line of sight from the highway to the houses or the receiver. After refraction of the line of sight, an additional noise reduction of about 1.5 dB can be achieved for each meter of the height of the barrier.

The barrier must be at least 8 times longer than the distance between the houses or the receivers from the highway. This will reduce the noise coming from the ends of the barrier more effectively [11].

However, the use of acoustic barriers has some disadvantages. There are no such barriers which can distinguish the noise which has to be controlled. Second, the placement of continuous walls is also a problem. The heavy wind load can also produce some structural problems in viaducts with ABs installed in the case of high speed trains.

The placement of classical barriers can involve high costs from technical and economical points of view. For all these disadvantages, installation of classical acoustic barriers could be unsatisfactory in urban areas for transport noise control. In the last decade, the discovery of new materials has led to the development of new devices for noise control. Sonic Crystals (SC) can be defined as periodic arrays of cylindrical acoustic scatters with radius $r$ separated by a predetermined lattice constant $p$, and embedded in air (figure 8b). SC performance is based on Bragg interferences due to a multiple scattering process [12], different from those previously known. As a consequence, there are frequency ranges, related to the periodicity of the medium, where the propagation of the waves is forbidden through the crystal. These frequency ranges are called band-gaps.

The first SCAS was theoretically proposed by [13], and the first prototype was designed and constructed by [14]. These devices are constructed using the Bragg interference as an unique damping mechanism and are formed by a set of solid reflectors embedded in the air. These screens are defined as the first generation of acoustic screens using sound crystal. However, the use of "bandgap zones" as unique mechanism for wave isolation is not enough to ensure a good performance of SCAS.

In recent years, the so called acoustic metamaterials have been developing, whose structure is characterized by periodic repetition of the shape of the structure and/or composites of building blocks or small elements of other materials intermittently located in one basic. The main advantages of the described metamaterials are the high degree of acoustic absorption by converting the sound energy into friction energy (and part of it in kinetic motion of built-in heavy elements) as well as the relatively easy design and synthesis of effective frequency acoustic sound absorption. In figure 9 a comparison between a second generation SC barrier and a classical acoustic barrier is presented. The acoustic attenuation in dB as a function of the frequency in Hz is clearly observed. A major disadvantage of the described metamaterials and structures is their high manufacturing cost, their relatively low mechanical strength and the need for a package to be incorporated in a number of cases.
Figure 9. Acoustic attenuation as a function of the frequency compared for second generation SC barrier and classical acoustic barrier.

2.2. 3D Sonic Crystals acoustic barrier COMSOL model

In order to check and optimize the experiment, we have created a COMSOL model of 3D Sonic Crystals acoustic barrier. The parameters of the COMSOL model are given in table 1. We have 3 rows with 7 noise isolating tubes.

We have used Pressure Acoustic Frequency Domain and Solid Mechanics to study the designed models. The finite element method is used where the complex area can be divided into a series of small interconnected subregions in which PDEs are approximately solved. Each sub region of the area is called an element and the process of dividing the object/domain into a finite number of elements is called sampling.

Figure 10. 3D model of a Sonic Crystal acoustic barrier:
1 – Acoustic receiver /microphone/; 2 – Surface around the sphere /Spherical Wave Radiation/; 3 – 3D Sonic Crystal acoustic barrier; 4 – Main surface of the Sonic Crystal acoustic barrier placement /Sound Hard Boundary/; 5 – Acoustic source; 6 – Front surface of the acoustic space /Symmetry/; 7 – Acoustic space.
Table 1. Design parameters.

| Parameter | Value     |
|-----------|-----------|
| Ls        | Distance between the barrier and the source 0.3 m |
| Lr        | Distance between the barrier and the microphone 0.4 m |
| Dp        | Tube diameter 0.16 m |
| dp        | Thickness of the tube walls 0.004 m |
| Hp        | Tube height 1.5 m |
| xp        | Distance between the tubes in direction source-receiver (x) 0.16 m x-axis (y) |
| yp        | Distance between the tubes in direction perpendicular to the 0.04 m |
| nr        | Row number 3 |
| nc        | Column number 7 |
| p_source  | Source pressure 1 Pa |
| Rair      | Radius of the acoustic area 2 m |

Figure 11 shows the row and column arrangement and the highest attenuation at 500 Hz and 800 Hz. It is the same for the other frequencies, so not all of them are presented in the publication.

Figure 11 shows Noise attenuation in dB at a frequency of 500 Hz and 800 Hz from COMSOL. You can see the arrangement of the noise barrier in 3 rows and 7 columns, as described in the geometry of figure 10. After the modelling we have obtained results that were used to perform the experimental setup (shown in figure 12) and the comparison between 3D Sonic Crystals acoustic barrier COMSOL model and Experimental setup.

3D Sonic Crystals acoustic barrier COMSOL model shows good attenuation over a wide frequency range. This type of noise barrier is applicable at medium frequencies.

Figure 11. Noise attenuation in dB at frequency of 500 Hz and 800 Hz.

2.3. Sonic Crystals acoustic barrier measurement
The experimental setup repeats the optimal configuration based on the COMSOL model. Figure 12 shows the experimental setup.
The parameters of the experimental setup that were used are those given in table 1. The data that are set in the model in COMSOL and those during the experiment are the same, as well as the set conditions. The distances to the source and the microphone are the same, as is the height when measuring. The material of the pipes, their dimensions and arrangement are the same as well.

A comparison of the results of the COMSOL model and the experimentally obtained result (figure 13) shows that at some frequencies there is a big difference in the obtained attenuation, such as at 50 Hz, 500 Hz and 1600 Hz. The difference is more than 30%.

In table 2 the obtained results are compared and the difference in % of the COMSOL model and the real experiment are presented.

![Figure 12. Experimental setup.](image)

![Figure 13. Noise attenuation as a function of the frequency from the experiment.](image)

| Frequency, Hz | COMSOL model Attenuation, dB | Experimental results Attenuation, dB | Difference in % |
|---------------|-------------------------------|------------------------------------|-----------------|
| 50            | 7.244018                      | 9.8242                             | 35              |
| 63            | 11.10373                      | 11.2729                            | 1.5             |
| 80            | 12.36799                      | 12.3915                            | 0.19            |
| 100           | 13.14756                      | 16.3877                            | 24.6            |
| 125           | 12.90293                      | 12.2052                            | 5.4             |

(continued)
Table 2. (continued)

| Frequency, Hz | COMSOL model Attenuation, dB | Experimental results Attenuation, dB | Difference in % |
|--------------|-----------------------------|--------------------------------------|----------------|
| 160          | 11.90689                    | 10.0146                              | 15.8           |
| 200          | 13.22491                    | 13.6792                              | 3.4            |
| 250          | 16.68946                    | 14.9856                              | 10             |
| 315          | 25.03462                    | 23.3149                              | 6.8            |
| 400          | 26.59061                    | 24.8455                              | 6.5            |
| 500          | 42.12851                    | 18.8721                              | 55.2           |
| 630          | 21.52336                    | 19.7586                              | 8.19           |
| 800          | 17.44579                    | 20.7058                              | 18.6           |
| 1000         | 16.70379                    | 17.4253                              | 4.3            |
| 1250         | 9.807703                    | 12.0346                              | 22.7           |
| 1600         | 13.15217                    | 17.5173                              | 33.1           |

The comparison between the two Sonic Crystal models, the designed and the experimental one, shows very promising results. The percentage difference between the two models at most of the frequencies is less than 10%.

3. Advantages and disadvantages

Sonic Crystal Acoustic Screens (SCAS) have several advantages over standard acoustic noise barriers:
- Use better and more advanced constructions of scatters. Various ways of controlling noise are used in these constructions. The presence of resonators allows for control of the resonance frequency and by changing the resonance geometry for control of the resonant frequency and even to have 2 or more resonance frequencies.
- The positions and distances between scatters in the sonic crystal array affect the bang gap, again by changing the geometry.
- Absorvent material is used, depending on the level of noise absorption.
- This type of barrier makes it possible to change the individual parameters and thus to correct and control only some noise control mechanisms. Depending on the type of noise, design the barrier at several levels and specify it. This will select a frequency range in which all noise control mechanisms will work and will be applicable to each type of noise. This advantage makes them highly competitive compared to classical acoustic barriers. SCAS may be designed on demand and used in various applications.
- With classic acoustic barriers mounted in the outdoor environment, the wind has a severely adverse effect, whereas in SCAS, the distribution and geometry allow the wind to pass without straining the barrier. Such a structure can solve structural problems at the classical acoustic barriers, which are further strengthened at their core against the impact of the wind.
- Another advantage of this type of acoustic barriers is their ability to position them both on the ground and in the air as their construction allows it.
- In SCAS, noise control methods are band gap, absorption and resonance frequencies. In this way a new technological procedure is introduced into the acoustic barriers. Their acoustic characteristics and reactions are pretty good compared to standard acoustic barriers. Therefore, these barriers can be used for protection in and outside cities to protect against traffic noise. Their open design and flexible structure designed for specific noises are the technological advantages of this type of barrier [10].

Acoustic noise barriers also have disadvantages:
- These types of barriers are more expensive than standard acoustic noise barriers.
- They are more difficult to design, several different features and parameters have to be calculated at the same time.
• The used materials must be studied and their technical characteristics as well as their aging and outdoor use must be known.
• They still do not have a common application like standard acoustic barriers.
• Their dimensions and size are much larger than those of standard barriers.
• Transporting them is difficult.

4. Conclusions
In this article we have presented a comparative analysis of the noise protection efficiency of standard noise barriers and type of sound crystals. Numerical simulations are presented in this study. One of the most commonly used solutions to reduce transport noise is the use of expensive combined noise barriers with a high degree of reflection and absorption. Sound crystals are a relatively new type of noise barrier under development and research. This article compares both types of barriers on the basis of their field of application, noise attenuation, their frequency range of application, production technology, maintenance, transport and price. Some of the results and characteristics are obtained by numerical simulations and experimental data, while others are obtained from published studies. Based on the obtained results, analyses and conclusions are made about the advantages and disadvantages of SC noise barriers and their application in comparison with the classic noise barriers.

The obtained results show that sound crystals can be used to improve the noise protection efficiency of standard barriers. There are a large number of materials on the market for the construction of noise barriers, including natural materials such as wood. Based on the results, one can think about designing new types of noise barriers, such as those that use sound crystals. In addition to new materials, we have investigated various shapes and arrangements of barriers in order to improve the attenuation of these noise barriers.

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References
[1] Mohsen S, Henry A S and Anton S R 2019 A review of energy harvesting using piezoelectric materials: state-of-the-art a decade later (2008–2018) Smart Mater. Struct. 28 113001 p 62
[2] Mechano Transformer Corporation 2006 A thin type piezo actuator: Macro Fiber Composite (MFC) http://www.mechano-transformer.com/en/products/mfc.html Accessed on: 15.06.2020
[3] Noh H M 2018 Acoustic energy harvesting using piezoelectric generator for railway environmental noise Advances in Mechanical Engineering 10(7) pp 1–9
[4] De Leo A, Marcocci S and Vanhooreweder B 2016 State of the art noise barriers in CEDR experience INTER-NOISE, Hamburg pp 4160–70
[5] Thompson D 2009 Railway noise and vibration (Elsevier) p 518
[6] More H 2020 Bravais lattices https://thefactfactor.com/facts/pure_science/chemistry/physical-chemistry/bravais-lattices/7443/ Accessed on: 15.06.2020
[7] Banov S and Kralov I 2003 Noise in transportation technics (TU-Sofia) (In Bulgarian) p 135
[8] Belnikolovski B and Abuid B 1994 On the dynamic characteristics of a mechanism with two-stage spur gears American Society of Mechanical Eng. (Petroleum Division PD) 64(7) 261
[9] Chong YB 2012 Sonic crystal noise barriers PhD thesis (The Open University)
[10] Peiró-Torres M D P, Redondo J, Bravo J M and Sánchez Pérez J V 2016 Open noise barriers based on sonic crystals. Advances in noise control in transport infrastructures Transportation Research Procedia 12th Conf. on Transport Engineering (CIT) (Valencia, Spain) pp 392–8
[11] Yankova A 2008 Noise barriers on highways Stroitel V(3) April (In Bulgarian)
[12] Chen Y Y and Ye Z 2001 Theoretical analysis of acoustic stop bands in two-dimensional periodic scattering arrays Phys. Rev. E 64 036616
[13] Kushwaha M and Rahnejat H 1997 Virtual prototype testing applied for non-linear dynamic analysis of a vehicle tailgate *J. Multi-body Dynamics: Monitoring and Simulation Techniques (Wiley-Blackwell)* p 315

[14] Sánchez-Pérez J, Rubio C, Martinez-Sala R, Sánchez-Grandía R and Gomez V 2002 Acoustic barriers based on periodic arrays of scatterers *Appl. Phys. Lett.* **81** pp 5240–42