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RESEARCH ARTICLE

Designing, constructing and testing of a new generation of sound barriers

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Abstract

Purpose Nowadays, noise pollution is considered a major environmental problem which has affected the health and comfort of millions of people around the world. Solving the mentioned problems need to design a new generation of acoustic barriers. Acoustics experts believe that stopping and absorbing the low-frequency sound is difficult. The aims of this study were to remove the harmful frequency in industries and cities. This study concentrates on the reduction of the noise level and increasing the mass law and resonance at low frequencies.

Methods Sound measurement and frequency analysis did to fix the harmful frequency in the Shiraz city and in the Shiraz Gas Power Plant. COMSOL 5.3a software used for simulation. Suitable material chose for the manufacture of the sound barrier through the Cambridge engineering selection software 2013. The meta-material sound barrier made and tested in the acoustic room and in the free space. Results analyzed and optimized by Design of Experiment (DOE) and Response Surface Methodology (RSM) software. Mini Tab. 18.1 software used for Statistical Calculations. New sound barriers manufactured with adding new strategies to previous studies to improve the performance of meta-materials like beautification inspired from the flowers of nature and increasing of resonance in internal pipes.

Results Three mechanisms used in this scatterer model which included, resonance phenomenon, Band Gap (BG) without absorption mechanism and inner-fractal-like structure. Our technique showed an advantage to reduce at frequencies below 100 Hz without adsorbent usage. The results showed that reduced noise exposures about 17.8 dB at frequency 50 Hz, about 9.1 dB within the range of 250 Hz according to EN 1793–2 standard (Lab

Highlights

Resonance phenomenon in IQFSCAB can reduce noise pollution.
The Stopping and Absorbing of the low-frequency noise is difficult.
Noise pollution is one of the most important environmental challenges in many countries.
New barriers have added a number of new strategies to previous studies.
Our technique shows a clear advantage to resonance at frequencies below 100 Hz without adsorbent usage.
Three mechanisms have been used in this scatterer model including resonance phenomenon, BG and inner- fractal-like structure without absorption mechanism.

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Test for Airborne Sound Insulation). The sound barrier reported in this work provides the best and updated solution in the field of noise control.

Conclusions A novel generation of sound barriers introduced. We called this structure Interior Quasi-Fractal Sonic Crystal Acoustic Barrier (IQFSCAB). In this study, several different gaps used to remove various frequencies. It could be concluded that the outcomes of the meta-material models based on the Sonic Crystal (SC) could be used for the purpose of noise control system and could be helpful for decision-makers on the noise control legislations.

Keywords Sonic crystals · Sound insulation index · Environmental pollution · Noise barriers · Noise control · Noise pollution

Introduction

Noise and sound are physically the same. The differences between these are due to the quality of the perceived sound of the listener. Noise is defined as an unwanted sound. Both sound and noise are similar in acoustics when propagate through air particles. From our point of view, one way to briefly classify acoustics science is to divide it into two sections, traditional acoustics versus new acoustics. In the history of science, traditional acoustics has an extensive background. Traditional acoustics started with the beginning of acoustics science and introduced in 1842 [1, 2]. As we know, the acoustics is basically divided into three physical phenomena, namely Production, Propagation and Reception. Almost all of the world researches follow one of these phenomena [1, 3]. Most applicable formulas in acoustics owe to their efforts and achievements. A new generation of the researchers tries to introduce a new trend in acoustics while applying the benefits of the traditional acoustics. In other words, the experts seek to integrate, align and adjoin physical phenomena in order to increase the potential of the mechanism.

"The Sound Scape" has defined as the full spectrum of sound that describes a city by Schafer. This range of sound originates from various sound sources. In fact, sound generators in a city are not just famous sources such as industries or cars. Other sources such as cell phones and music can be considered [4].

One of the most primary targets is reducing sound in the source by acoustics experts and noise control designers. It is the best way to radically control and remove annoying noise. The goal of the classic urban noise management is mainly reducing the level of unwanted noise by reducing the number of generating sound sources and limiting its propagation path. Unwanted noise is often generated by mechanical or electronic mechanisms in the city. This has always been the subject of protest by users of noisy generators. Unfortunately, controlling strategies often occurs after happening the problems because of spending high costs. This solving process has been the most common way to control the noise in Iran from past to present due to the lack of scientific information on meta-materials. No doubt, this common way is not suitable for noise control. The comfort of the people is lost due to the failure of the industry owners' attention. These owners resist not to cost about noise control. Public and environmental organization complaints have increased; furthermore, there is a force that tries to reduce remarkable cost of noise reduction in the current dynamic society. As a matter of fact, noise reduction was not definitely possible for many of our non-modern cities due to financial reasons such as research costs, project turnover and the like. In fact, an innovative approach is required to solve the problem.

In the past, traditional acoustics used highly dense materials like concrete with a density of at least 1800–2900 kg/m^2 to eliminate the limited frequencies. In this case, heavy walls have no frequency choice property. If it is not possible to reduce the noise at the source, it should inevitably be prevented in the direction of the noise transferring to the listener.

In the late 80$_s$, Yablonovitch and John (1987) simultaneously triggered the primary attention in periodic systems due to the interesting propagation properties of the electromagnetic waves inside the periodic systems. The ability to exploit the propagation properties of electromagnetic radiation have produced a number of practical applications such as modifying the spontaneous emission rate of emitters [5, 6], slowing down the group velocity of light [7, 8], designing highly efficient nanoscale lasers [8], enhancing surface mounted microwave antennas [9], sharp bend radius waveguides [10], efficient radiation sources [11], sensors [12], and optical computer chips [13]. All of these examples are just one of the most important achievements in the periodic systems.

A few years later at the beginning of the 90$_s$, an increasing interest materialized in the survey process of acoustic wave propagation on periodic arrays. Primary theoretical predictions [14, 15] and experimental results [16] motivated explaining the propagation properties of these periodic arrays that could filter noise. A number of researchers have named these periodic arrays as a sculpture. John Pendry introduced the negative refractive index. Then, several researches recommended different kinds of meta-materials to achieve locally resonant acoustic materials with negative properties like cylinders with cross-section split ring as building blocks [17], Helmholtz resonators [18, 19] or C shaped resonators [20].

The double negative material was adducted by Li and Chan [21]. Previous analytical methods work accurately when the geometries of the scatterers are determined well and their radiation pattern can be described by well-known functions. Recent works of Umnova et al. [22], Martinez-Sala et al. [23], and Romero et al. [24] developed the improvement of the attenuation properties of the scatterers. The application of sonic crystal (SC) as the acoustic barrier has made increasing interest in the recent years. Furthermore, SC with resonant properties and absorbent materials have been investigated by Umnova et al. [22].

Propagation of waves inside periodic structures has yielded increasing attention in the last years [25–30]. The interest of the SC has concentrated on increasing their acoustical focalization [31] and attenuation properties in the last years [22, 32].

Nowadays, wave propagation in periodic media has especially been investigated in many branches of science and technology such as, solid-state physics [33–35], water waves [36], electromagnetic waves [37, 38], acoustics [1, 37, 39, 40], elastic media [32, 41–43] and seismology [44–46]. A wide range of mathematical techniques are now available for solving of the problems, including the interaction of waves with scatterers inside these crystals.

Although, most research is based on photonic (light), Information Technology (IT), or other scientific aspects, the efforts to maximize the capacity of meta-materials and its improvement have been accelerating [46, 47]. It seems that most researches on acoustic meta-materials have been done by Constanza Rubio, Romero et al. at the University of Valencia [48–55].

Description of first generation of parameters and definitions of Sonic Crystals Acoustic Screens (SCASs)

An acoustic meta-material or SC is a structure designed to control, block, trapping and manipulate sound waves as these might occur in gases, liquids, and solids. The historical record into acoustic meta-materials follows from theory and research in negative index material by John Pendry [45, 46].

There has not been a single definition of the discussion of meta-materials, and especially sonic crystal in scientific articles, or books, but SCs are periodic arrangement of scatterers, whose interaction with acoustic waves leads to the formation of the Band Gap (BG). The BG is used in many applications such as sound barrier, frequency filter, acoustic imaging and the like. Meta-materials can be designed and constructed periodically, symmetrically, asymmetrically, with regular and irregular shapes. Meta-materials artificially make. It seems that any structure that embodies meta-material requirements can be considered as a SC structure in acoustic wave [54, 56].

Several parameters quantitatively measured the improvement of the properties of the used SC. Some of these parameters include the Insertion Loss (IL), the Attenuation Area (AA), the Fraction of Vacancies (FVs).

IL defines as the difference between the sound level which recorded at the same point with and without the sample. The effectiveness of a road traffic noise barrier is measured by the IL.

$$IL(dB) = 20\log\left(\frac{p_{direct}}{p_{\text{interferred}}}\right), dB \qquad (1)$$

Area of spectrum obtains from the frequency response produced by the distribution of scatterer. It defines as the area enclosed between the positive spectrum and the 0 dB threshold in the selected frequency range. If the area of spectrum is measured from the attenuation spectra, the parameter is called attenuation area, (AA), and if it is obtained from the pressure level spectra, it is called Focusing Area, (FA). An increasing in the value of these parameters implies an improvement in the attenuation or focalization properties of the system. Attenuation area parameter has been used in several works [24, 51] in order to measure the attenuation capability of a distribution of scatterers. FA is also used for characterizing the focalization capability [53]. Another parameter is a Lattice Constant (LC) or lattice parameter, refers to the physical dimension of unit cells in a crystal lattice. The distance between identical points in two of the corners of the unit cell. In some scientific papers, this parameter is defined as a distance between two parts, or two edges, or two cavities or locations of defects in the structure of the meta-material. Therefore, the value changes from zero to a certain amount that does not damage the periodicity of the structure.

The LC means the determined distance between meta-materials which is periodic or non-periodic. LC has a tremendous impact on reducing or increasing the amount of reflection and transmission of waves after contact. Fractal structures are a geometrical or physical structure having an irregular or fragmented shape at all scales of measurement. These structures from the greatest to smallest scale have certain mathematical or physical properties. Fractals are encountered ubiquitously in nature due to their tendency to appear nearly the same at different levels, as is illustrated here in the successively small magnifications of the Mandelbrot set [57].

The Band Gaps' mechanism is created from the formation of longitudinal gaps with determined width in a meta-material barrier. This controlling feature allows to reach the selectable frequency by changing gap, length and width. These parameters will help us to describe the acoustical properties of the SC.

Materials and methods

This study introduces a new innovative way to acoustic experts. This new innovative way causes that the sound and acoustic engineers consider beauty, the noise control and ease of implementing at the same time [58]. Common methods are not accurately able to study the sound with the complexity of engineering systems and the enhancement of the effective mechanisms within their components. There are several software among the methods of engineering and theoretical mathematics that are used for describing different sound behaviors, such as Multiple Scattering Theory (MST), Method of Fundamental Solutions (MFS), Finite Element Method (FEM), and software like Ansys, Comsol, Abaqus, Hyper Mesh and the rest. These software have their own unique characteristics, but are more likely to be used for scientific researches and are not sufficient for laboratory surveys. It just seems to boost results along with laboratory tests.

In our research project, steps of the new barrier design method are as follow:

- Sound measurements and frequency analysis to determine the harmful frequency in Shiraz and in an industry (Shiraz Gas Power Plant)
- Simulation of acoustic meta-material with COMSOL 5.3a software to remove the harmful frequency that has the highest level of sound pressure level (L_PC).
- Choosing the suitable material for the manufacture of meta-material barrier through the Cambridge Engineering Selection software 2013 (CES 2013)
- Making the meta-material barrier and testing it in the acoustic room and in the open space
- Analyze the results and optimize it by Design of Experiment (DOE) software
- Analyze the results and optimize it by Response Surface Methodology (RSM) software

Shiraz city is known as the main cause of noise pollution. First, the traffic jam places identified in cooperation with the traffic center of Shiraz. Second, sound level meter and frequency analysis was carried out at 202 places from different parts of Shiraz. Figure 1a shows frequency analysis in one-third-octave band weighting network in the fast mode at Shiraz Gas Power Plant in 2016 and 2017. As shown in Fig. 1b, the harmful frequency of Shiraz traffic jam was 50 Hz and about 83.3 dB. Figure 1b shows the amount of changes in the sound pressure level (L_P,C) in a one-third-octave band measured in the fast mode at 10 traffic jam stations in 2016 and 2017 in the metropolitan station in Shiraz city. The Shiraz gas power plant was simultaneously considered as a noise generating industry. In this regard, sound pressure level measuring and frequency analysis were carried out and frequency was below 50 Hz with 115 dB. These two frequencies were determined as the disturbance frequency and the prevailing sound pressure level [59].

In fact, the comparison was made with Iran's Environmental Standard (55 dB/day and 45 dB/night) and the results were higher than the environmental standard value at the day and the night.

Subsequently, scientific texts on noise barriers and new structures were reviewed [1, 5–46, 48–55, 58, 60–66]. In this project, acoustic meta-materials or SC were selected as noise barriers. These barriers were called the Sonic Crystal Acoustic Barriers (SCABs). SCABs are among the advanced structures of the last two decades to eliminate and control the noise. It seems that in 2002, the first structure of SCAB was introduced by Sanchez Perez et al. [54]. Some of the important properties of SCABs can be referred to as the (BG) or Frequency Selective Deletion (FSD) property. These properties are one of the most unique features of SCABs' arrays. FSD is referred to as BG in scientific texts. BG feature is a mechanism in which the frequency or range of frequencies is not allowed to pass. In other words, frequencies are concealed and deleted (see Fig. 2).

The absorption process is inherent in the material. This process performs by using absorbent materials. Each material will have an impact on the method of effect and the amount of reduction, depending on its absorption characteristics. Figures 3 and 4 show that it is very difficult to remove low frequencies with absorbent materials [2, 3]. In a study conducted in Italy on various granules of recycled tires, it showed that at frequencies below 200 Hz, a maximum absorption of 10% is obtained in thicknesses of 3 to 4 mm of rubber. In another study on bamboo granules, approximately the same numbers are observed. As a matter of fact, research on absorbent materials or their optimization continues [3, 67].

The combination of engineering methods and absorbing materials can be effective. A novel periodic or non-periodic system introduces with internal complex environment, containing an array of fractal-like engineering geometries (Quasi-Fractal) as aerial diffusers embedded in the air.

The first arrays made are called SCASs and then renamed to SCABs. Apart from assigning different names to it, this system is effective in removing and controlling the noise.

All of the properties are considered in new barriers, including mechanisms and physical phenomena in a meta-material that create tremendous properties. These properties are called "Tunability Property" or Frequency Selective Service (FSS). From the technological point of view, tunability allows the barrier to remove the selected disturbing frequency. The common phenomena in tunability can operate independently and simultaneously, including Absorption, Resonance, and BG. All of these mechanisms cause to reduce the noise pollution. It is also possible to use one or all of the mechanisms. The properties of each of the above mechanisms depend on the BG, the type of absorbent material, the type of design, the size of the pipes and their lattice constant. Indeed, it is possible to customize the type of structure according to the need.

Material selection with CES software

It was required to select material for construction. Therefore, in this study, Cambridge engineering selection software

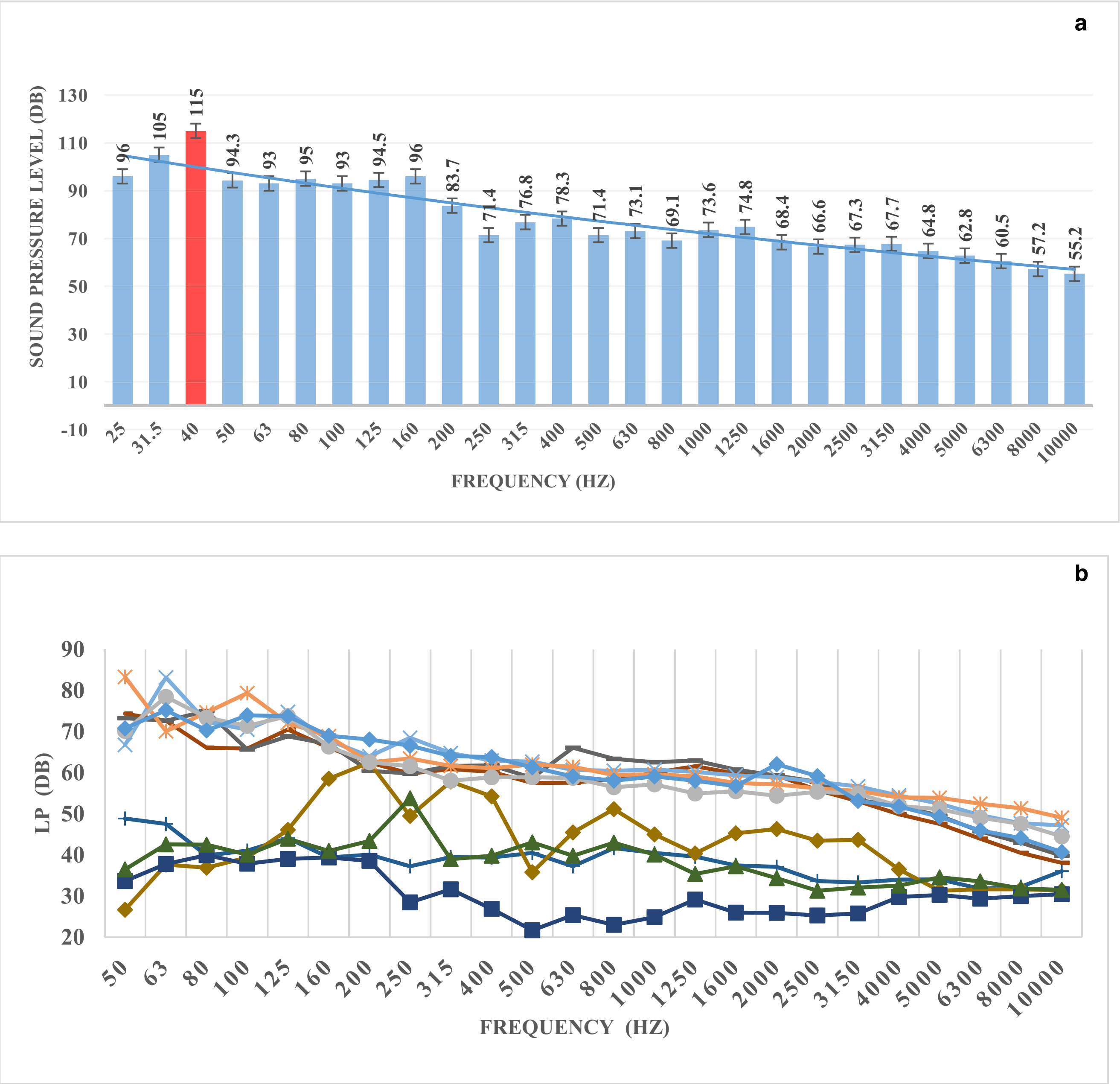


Fig. 1 **a** Sound pressure level changes (L_P, C) one-third-octave band weighting network in fast mode at Shiraz Gas Power Plant measured in 2016 and 2017. **b** Sound pressure level changes (L_P, C) in one-third-octave band weighting network in fast mode at 10 stations measured in 2016 and 2017 in Shiraz city

version 2013 was used to select the appropriate material for designed structure. This software has different material libraries and has divided into three different material levels with their comparison. Polyvinyl chloride (PVC) chose as the main material of the meta-material structure according to the output of this software and the considered features. There was a need for a material with the lowest volumetric modulus, the highest possible density and minimal of propagation speed in sound waves simultaneously (Fig. 5).

The density limited to a minimum of 1000 kg/m^3 and the volume modulus range to a maximum of 1.5 GPa to find the second case. 67 items remained after applying these limitations, including foam, ceramic, PVC, elastomer and composite from among 4200 materials inside the database (Fig. 5). Finally, PVC was selected for metamaterial as a best material.

Simulation of acoustic meta-material with COMSOL 5.3a software

Firstly, scientific texts and the pervious simulations' results of COMSOL software were studied. Then, we

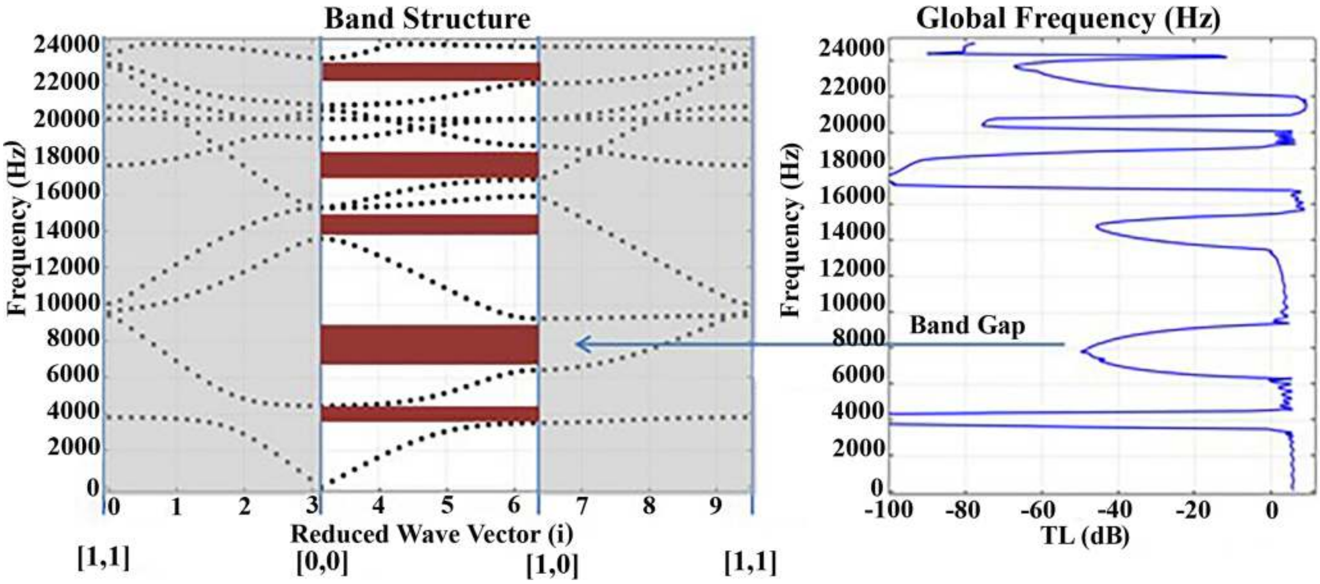


Fig. 2 Output results of the band structure resulting from the analysis of the energy loss chart using COMSOL 5.3a software. The brown rectangles are banned strips of the BG

simulated some shapes, pipes with different diameters and different arrays of pipes as you can see in Figs. 6 and 7and section c in Fig 15. After our simulation, it was found that the removal of low frequencies was not easily possible, even with the addition of the number of small pipes, using of different pipe sizes, external reflection control and gap change in the smaller pipes. We offered a new idea that by inserting small pipes into the large pipe, it may lead to the removal of low frequencies Figs. 13 and 14. Therefore, a special meta-material designed with small internal pipes and symmetric or asymmetric gaps. Figures 13 and 14 shows these structures. The designed SCAB is made of three main pipes, including two or three acoustic meta-material with small pipes as interior fractal-like. They arranged in a linear array without the LC spacing as you can see in Figs. 13 and 14. We called this structure as “interior quasi-fractal sonic crystal acoustic barrier (IQFSCAB)” due to fractal-like interior and exterior pipes like those seen in some of the flowers in nature. Two models of IQFSCAB, including IQFSCAB 1 and IQFSCAB 2 were made in this study. With explained new idea characteristics, the first BG at zero angle caused the wave be observed at a frequency of 385 Hz at IQFSACB 1 and at a frequency of 125 Hz at IQFSACB 2. These results were low frequencies and could also be reduced to lower ones.

Optimization the results with DOE software

After simulation by COMSOL 5.3a software, sixty tests were performed in the acoustic room and free space (Fig. 15). Then, DOE software was used to analyze and optimize the number of experiments. This software tests 100,000 experiments and displays the results (see Figs. 8 and 9). The effective parameters on the performance of the meta-material barrier function are optimized. The cube of parameters was optimized for the parameters affecting the barrier performance. Figures 8 and 9 showed the results of this optimization.

Construction of PVC pipe as an acoustic meta-material and resonator

So far, the worldwide researchers have been able to reduce the frequency around 300 Hz. Therefore, we tried to design a new structure in order to further elimination and reduction at lower frequencies in this barrier. The new structure tested in the acoustic room after designing it. The largest pipe size was chosen according to previous scientific literature and outputs of CES 2013 and COMSOL Software. Different pipes were prepared in sizes of 125, 160, 315 mm of semi-strong PVC pipe type. All these pipes are the largest and smallest common size PVC pipe manufactured in Iran. The analysis of the loss-rate diagram showed that when the size of the loop became larger, the resonance frequency reduced to about 200 Hz and a loss rate of about 100 dB (Figs. 2 and 10). The larger ring also absorbed in large region at 500–1000 HZ about 100 dB. In fact, it could be concluded that we needed to use larger size loops to achieve the optimal structure and absorb low frequencies [68].

The PVC had the features of an appropriate barrier to cover the physical mechanisms of this structure during the use of fractal-like geometry. Frequency analysis and sound pressure level carried out in the existing acoustic room. Characteristics

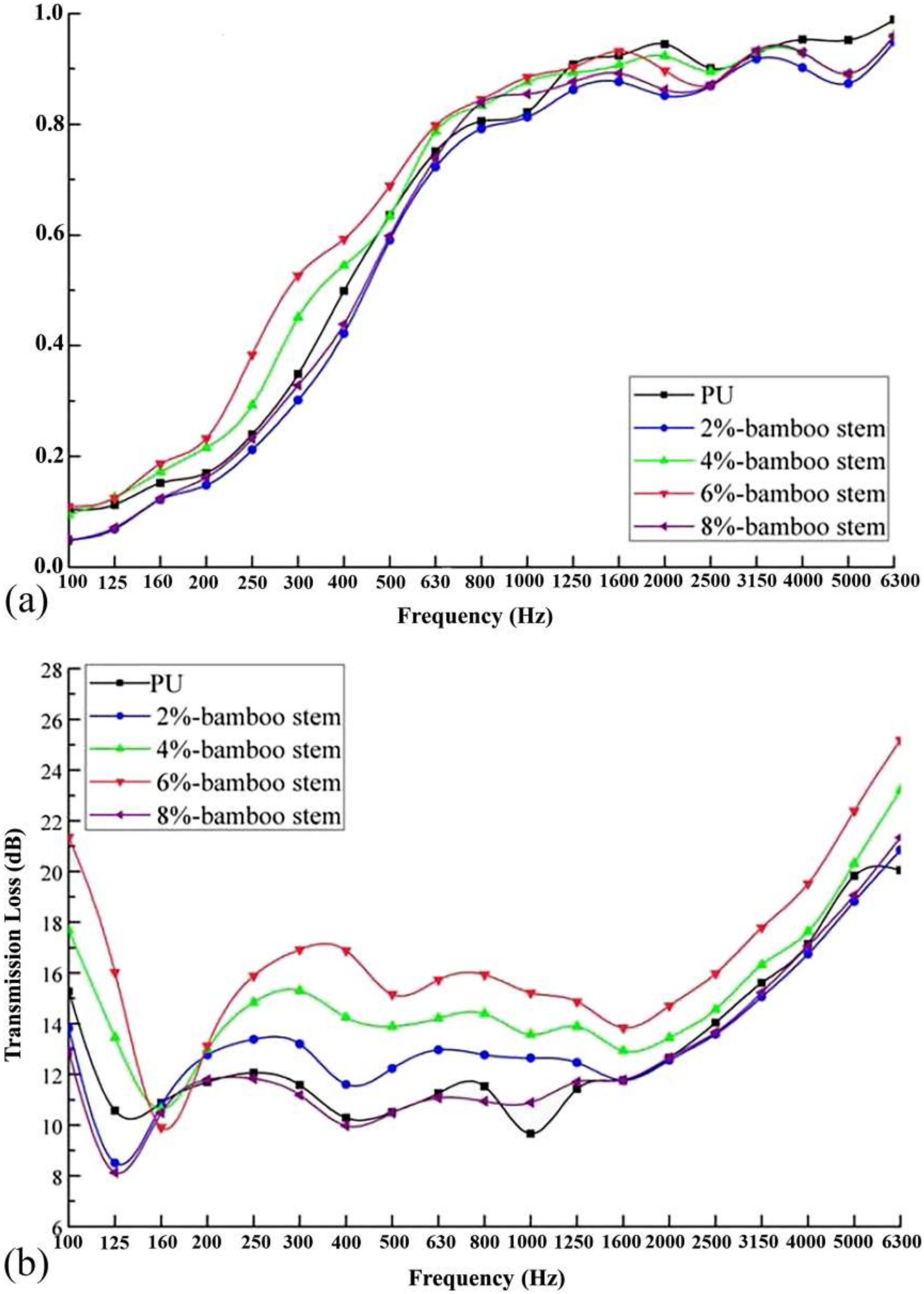


Fig. 3 **a** Sound absorption coefficient and **b**) transmission loss of PU foam composites with 3–4 mm bamboo stems [2]

of the acoustic room calculated with the existing equations. Then, design of the experiment was done. You can see the position and array of PVC barrier in Figs. 11 and 13 and Fig 15.

The designed SCAB made of cylindrical PVC, with the internal radius of 0.3073 m, with the thickness of the rigid wall 0.0077 m and a BG along its entire length with a slit of

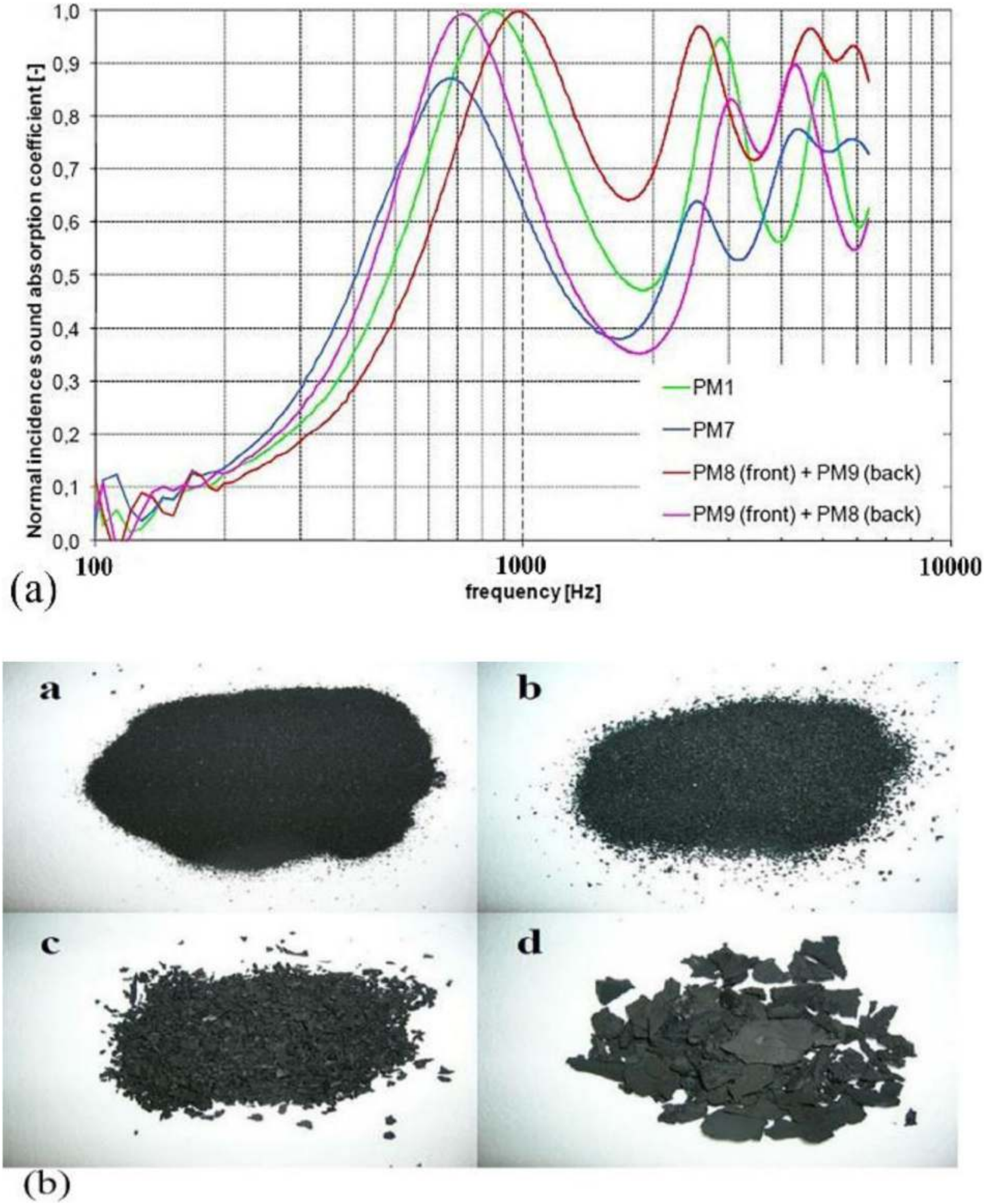


Fig. 4 **a** Sound absorption coefficient spectra of samples PM1, PM7 and of the two composite samples **b)** The rubber granules derive from the chipping and winnowing of use tires (a "small" size (average diameter of the granules = 1 mm) and a "medium" size (average diameter of the granules = 3 mm) [3]

about 0.1 m. The above-mentioned cylindrical pipes investigated with external radius of 0.315 m and height of 2 m in constructing two different structures of the SCAB. In this structure, firstly, four tests were designed and implemented to obtain the necessary information from the new barrier by us: A) inside the IQFSACB 1 structure, the same pipes with an internal radius of 0.1218 m made of cylindrical PVC and with the same slit equal to 0.03 m were used; B) inside the IQFSACB 2 structure, the non-uniform pipes with internal radius of 0.1218 and 0.196 m made of PVC but with the same

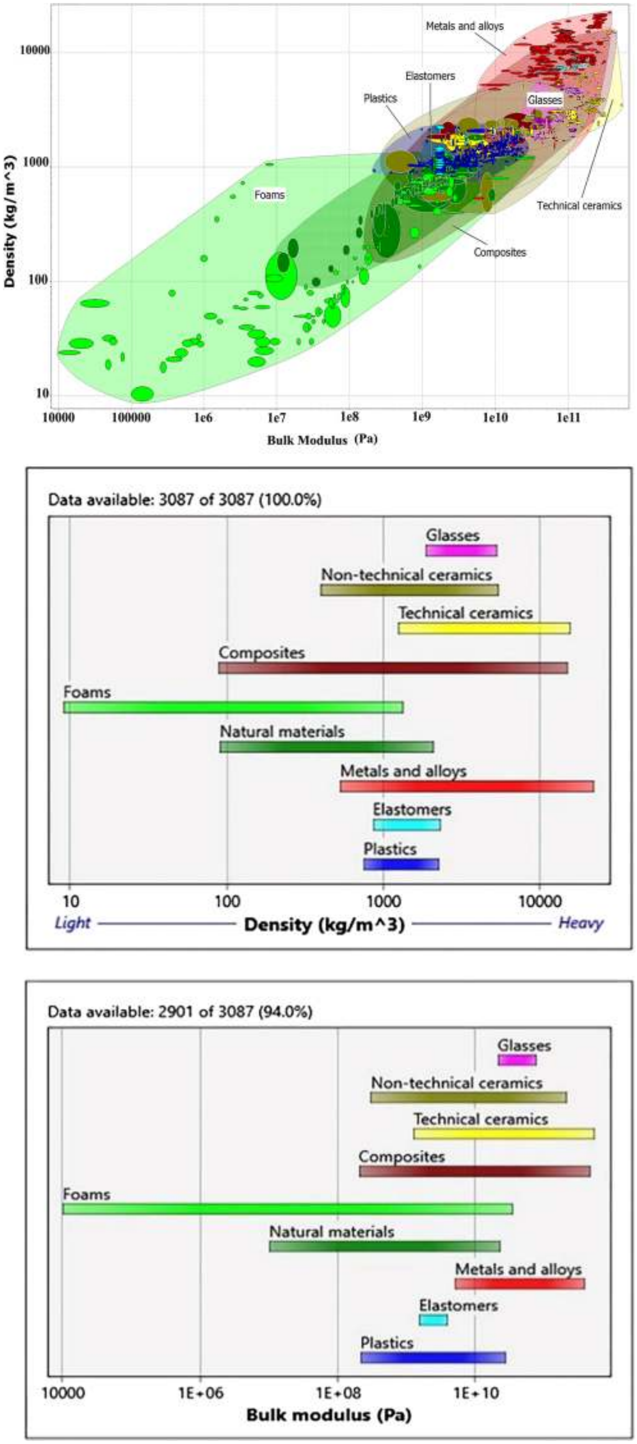


Fig. 5 The volumetric modulus, density range of materials based on their main family derived from the CES Engineering Materials Database Software 2013

slit equal to 0.03 m as a BG along its entire length, then data were extracted. The thickness of the internal pipes in the IQFSACB 1 structure was the same and equal to 0.0032 m and in the non-uniform IQFSACB 2 structure was 0.0032 and 0.1951 m. Two new experiments conducted to investigate the effect and reflection that resulting from the external fractal geometry in the vicinity of the IQFSACB 1 and IQFSACB 2 barriers. C) The gap of pipes located at the outer fractal geometry with slit of 0.03 m were tested in both new structures.

All slits and BGs performed with a CNC (Computer Numerical Control) machine in different pipes, the angle of attack and the sound wave entering to the IQFSACB 1 barrier was 0 to 30 degrees and the IQFSACB 2 barrier was 0 to19 degrees to achieve the result with higher accuracy (See Figs. 11 and 15).

The structure of IQFSCAB consists of two parts: 1. external core, 2. Internal core. The external core of a cylindrical PVC with a gap about L = 100 mm along its entire length is 2 m. External cylinder acts as an internal structural supporter for smaller pipe and performs some part of the resonance and diffusion process. The interior part of the larger pipe has a triple function. IQFSCAB is easy to install and has cost reduction because of its plasticity comparing to iron or the like.

In fact, the inside part including small pipes acts as an internal resonator and affects on a low and moderate frequency range. In this structure, resonance and reduction of the low frequencies are targeted considering the different length gap in the internal pipes.

Acoustically, all physical phenomena separately happen inside the internal fractal-like core of IQFSCAB. In fact, some new creations in this structure of the meta-material considered and investigated. All physical phenomena in the IQFSCAB 1 and 2 and different arrays of pipes were investigated with advanced electronic equipment such as an oscilloscope to see and survey the waveform (see Fig. 12).

Absorbent

According to previous research, porous materials are generally effective in the intermediate frequencies range. In this study, some adsorbent-material coating used and tested as absorbent in the new meta-material structure such as Glass wool, Rock wool (Fig. 19).

Figures 12, 13 and 14 show IL measurements for absorbent and non-coating structures. According to the standard 1793–1: 1997, which specifies the position setting of the sound-level-meter and microphones, five microphones are located at the points a1 to a5 during exposure to this sound generator. A surrounded sound source is used during measurements that has the ability to produce frequencies from 50 to 16,000 Hz and is in the C position. But the frequencies that studied in this investigation conducted from 20 to 5000 Hz (see Fig. 12).

The required sound produced by a sound source and reinforced by the amplifier in this acoustic room in the emission part (one of two parts of the acoustic room). The sound level decreased about 17 dB in the receiving part (the other part of the acoustic room after the barrier). A

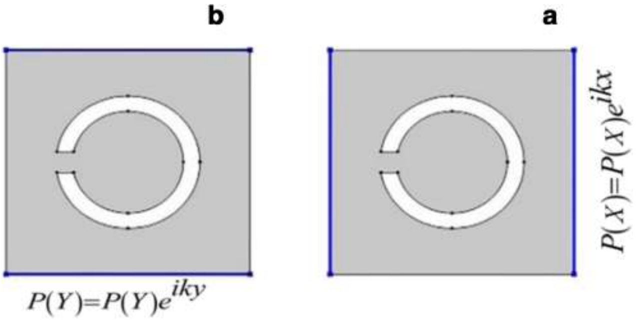


Fig. 6 Single cell boundary conditions [67]

series of experiments was conducted in a semi-echoic chamber (acoustic room) to validate the results obtained from this design. The room size was 2*6*2 cubic meter, which simulates the free space conditions Fig. 15. Sound pressure level and frequency analysis were carried out in this acoustic room. These results indicated the level of intrusive background noise. The electronic equipment was used to generate, receive and analyze sound in these experiments according to Table 1.

This room had five microphones located at a distance of 1 m in the back of the barrier and a VOX, an American audio source generator as a sound source that is located at a distance of 1.2 m in front of the barrier. Two amplifiers were used to enhance the sound before and after the barrier in all experiments (See Table 1).

Determine the applicable sound standard

In this study, the standard text EN 1793–2: 1997 (Lab Test for Airborne Sound Insulation) were used. The sound absorption coefficient calculated as an estimation of the acoustic absorption or absorption sound evaluation index (DL) for the proposed structure according to this standard. The value of DL index was used to classify the barrier with respect to its acoustic absorption characteristics [69].

This standard evaluates the intrinsic natures of the noise barrier relative to the airborne noise insulation. The measurement mechanism and technical calculations are specified in the standard EN 1793–2:1997. In this research, the evaluation parameter of the airborne noise insulation DL_R computed according to the standard EN-ISO 10140:2011 (ISO, 2010). Measures accomplished in the acoustic room which is located at Shiraz Gas Power

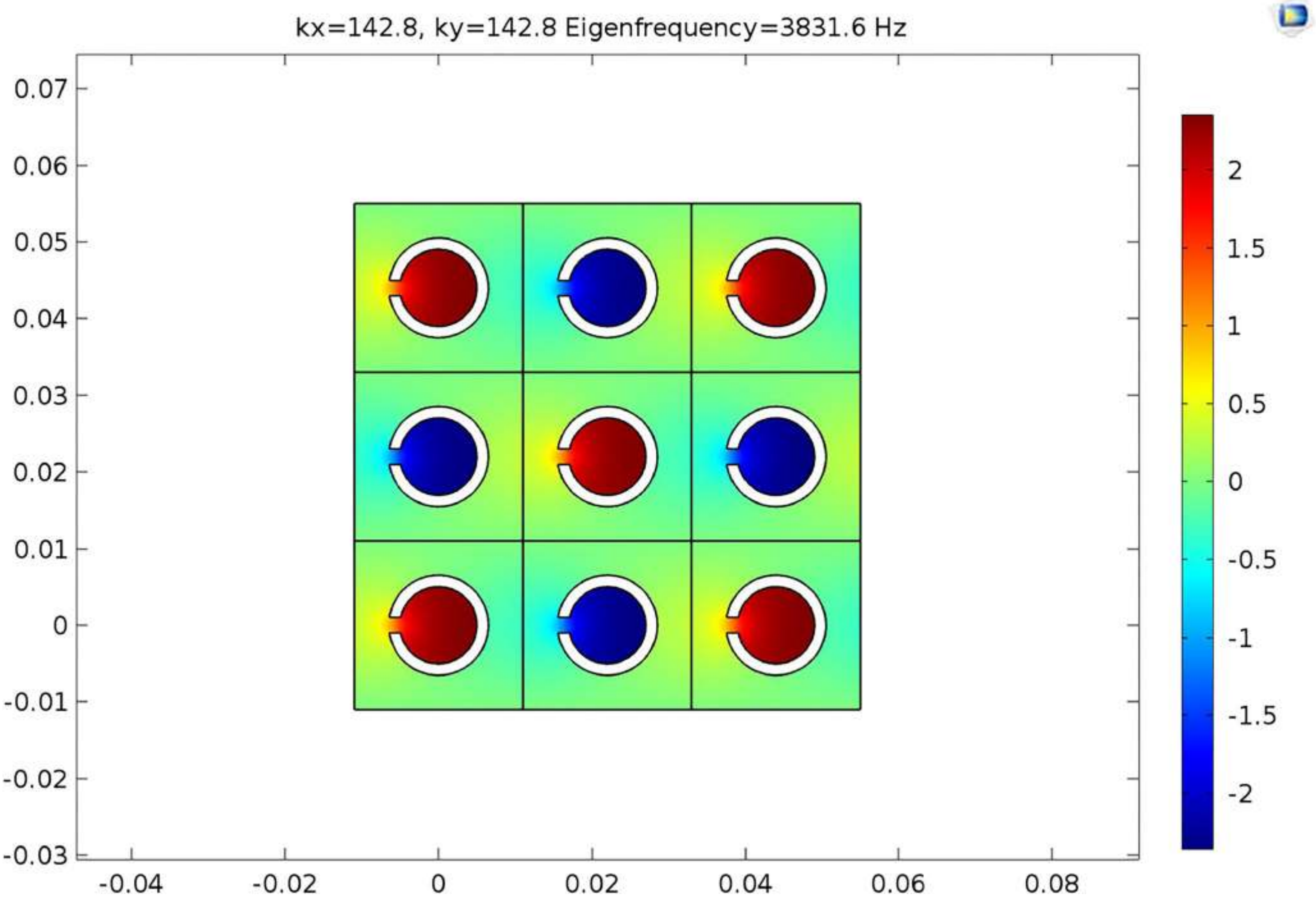
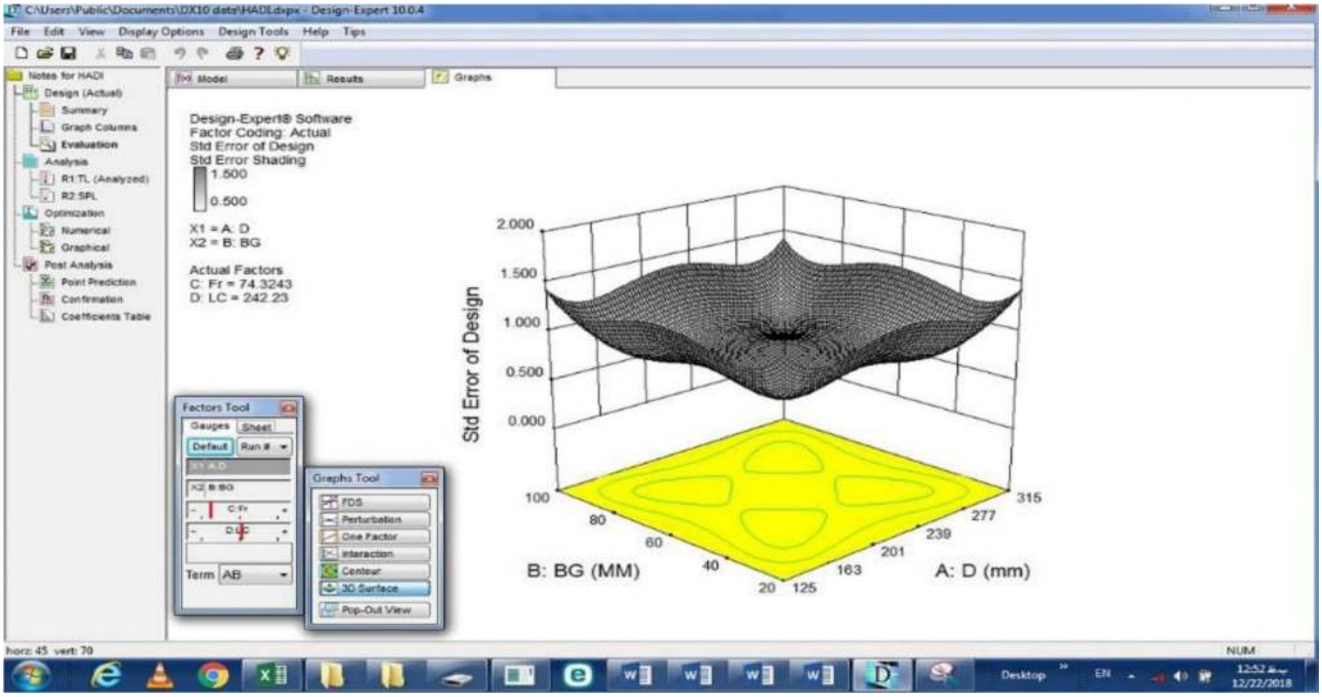


Fig. 7 Acoustic pressure diagram of a meta-material sample simulated with COMSOL 5.3a software at resonant frequency 3831.6 Hz



Design-Expert® Software
Factor Coding: Actual
Std Error of Design
Std Error Shading

X1 = A: D
X2 = B: BG

Actual Factors
C: Fr = 74.3243
D: LC = 242.23

Fig. 8 The optimal results of the pipe diameter (D) with the band gap by the RSM method in the DOE software. Diagram of the results of analysis and optimization of pipe diameter with BG. An analytical representation of the results of the analysis and optimization of pipe diameter with bandwidth and standard deviation of data. For example, this figure shows that the best distance to remove the 74 Hz frequency is 242 mm in LC

Plant. A series of experiments conducted in a semi-echoic chamber (acoustic room) to validate the results obtained from this design. This research tried to make a real space for sampling. The analyzed IQFSCAB located in the middle of an acoustic room, dividing it into two equal parts. In the emission part (one of the two parts of the acoustic room), a sound pressure level generated. In the receiving part (the other part of the acoustic room), the sound pressure level was 17 to 23 dB lower than the sound source generator in some evaluated frequency bands from 20 Hz to 4000 Hz. With these conditions, the sound pressure level measured in 2 parts, in the emission part (L_1) and

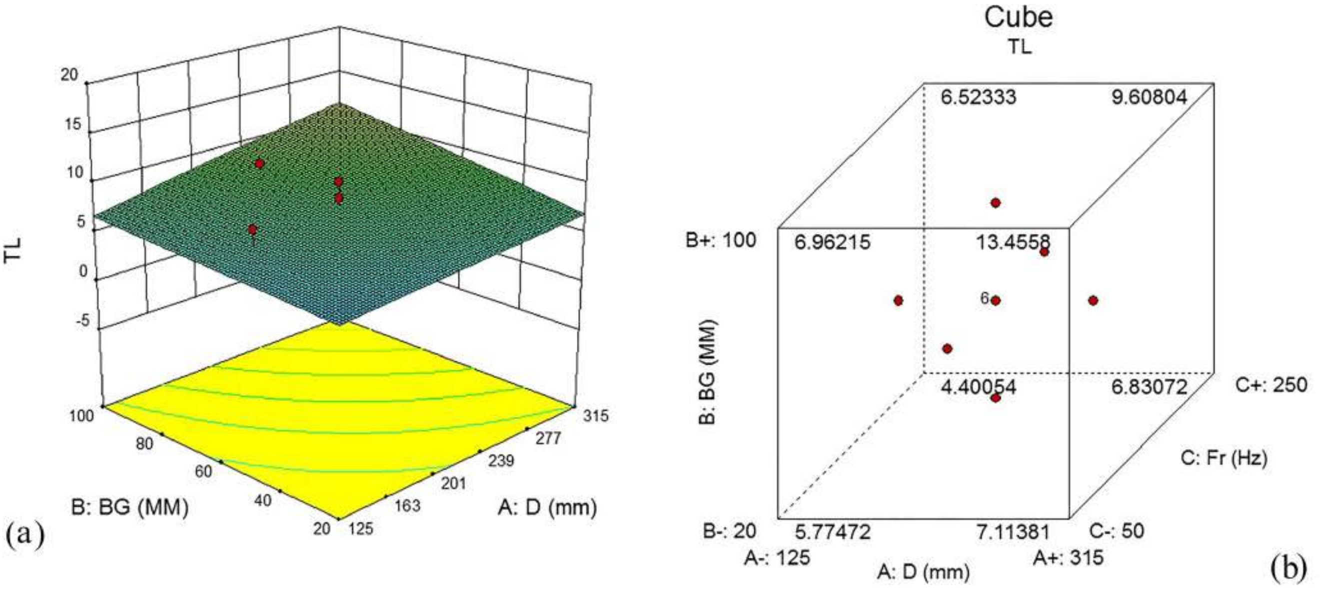


Fig. 9 Results of cube optimization of parameters of meta-material acoustic barrier made of PVC pipes **a)** Three-level optimized diagram about Transmission Loss (Insertion Loss), Diameter and Band gap produced by RSM Method in DOE Software **b)** Three-variable cube produced by RSM Method in DOE Software

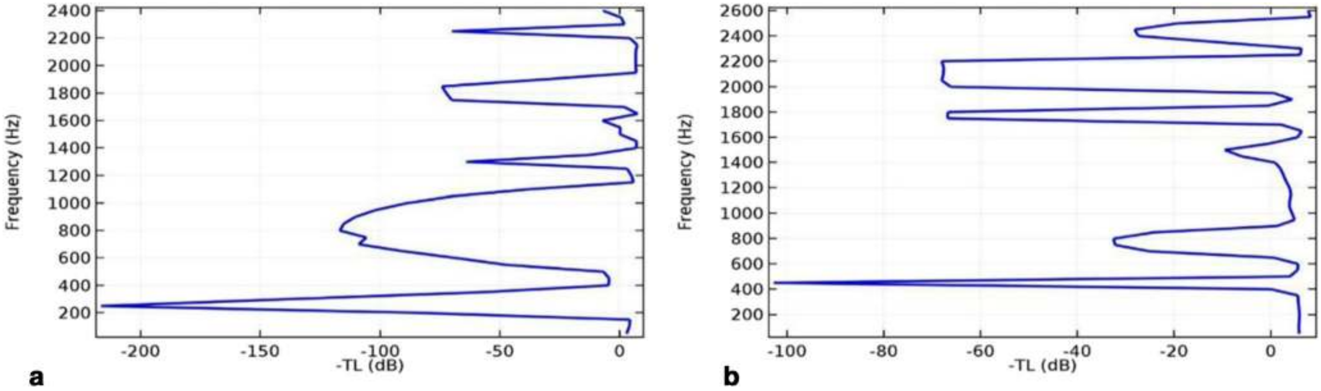


Fig. 10 Loss Amount of Sound Wave **a)** Smaller Pipe **b)** Larger Pipe by 2D simulation in COMSOL Software 5.3a

in the receiving part (L_2), for five positions of the microphones. With the averaged level of these two sections, the difference (D) can be calculated with the Eq. 2:

$$D = L_1 - L_2 \tag{2}$$

It is required to correct this factor based on some other parameters, such as the reverberation time (T), the volume of the reception acoustic room (V), the common surface of separation between the two parts of acoustic room, i.e. the surface of the sample (S). Thus, the acoustic reduction index R will be:

$$R = L_1 - L_2 + 10\log\left(\frac{ST}{0.163V}\right) \tag{3}$$

The final calculation of DL_R is as following equation:

$$DL_R = -10\log\left|\frac{\sum_{i=1}^{18} 10^{0.1L_i} \times 10^{0.1R_i}}{\sum_{i=1}^{18} 10^{0.1L_i}}\right|, [dB] \tag{4}$$

where L_i is equal to the noise level for each third octave band of the normalized traffic noise spectrum given by the standard EN 1793–3: 1997. Measuring this index can be the basis for the decision to evaluate this barrier [57].

Our proposed structure with $DL_R = 17.8$ dB is located in the category B_2 (see Tables 2 and 3). It is generally agreed that these categories are too wide for practical use. Most traffic jam projects would require B_3 giving a DL_R of at least 25 dB. For low frequencies, B_2 can be sufficient, but it is important to specify a DL_R level of at least 20 dB [68, 69]. Considering the acoustics' point of views, a non-absorbent acoustic barrier created from several PVC-based cylinders in our research can compete with traditional acoustic barriers formed by continuous and dense systems. The performance of IQFSCAB is obtained with the largest radius of the existing PVC pipe in market of Iran to seek for the expressed capabilities. Larger pipes can probably control lower frequencies.

Discussion

Today, the reason for neglecting the issue of noise pollution has been more attention to air pollution in the most major

Fig. 11 Workshop area shows how to create CNC and necessary gaps in different size pipes to make IQFSCAB structures

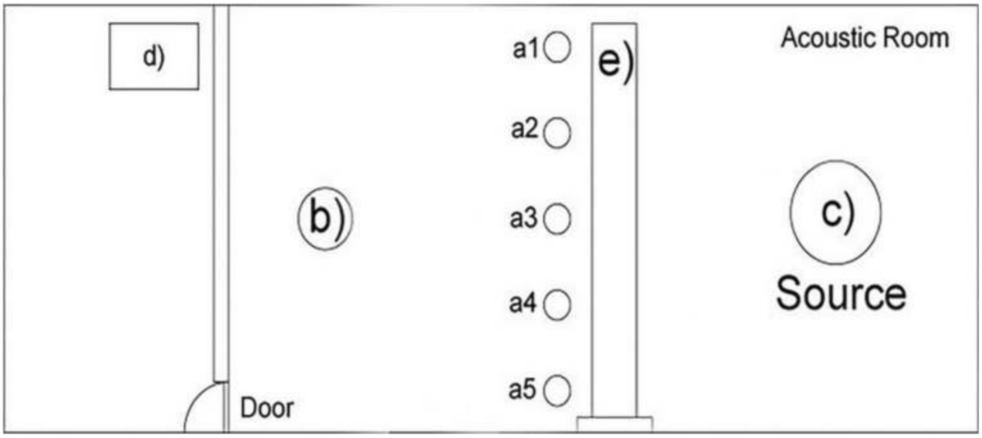
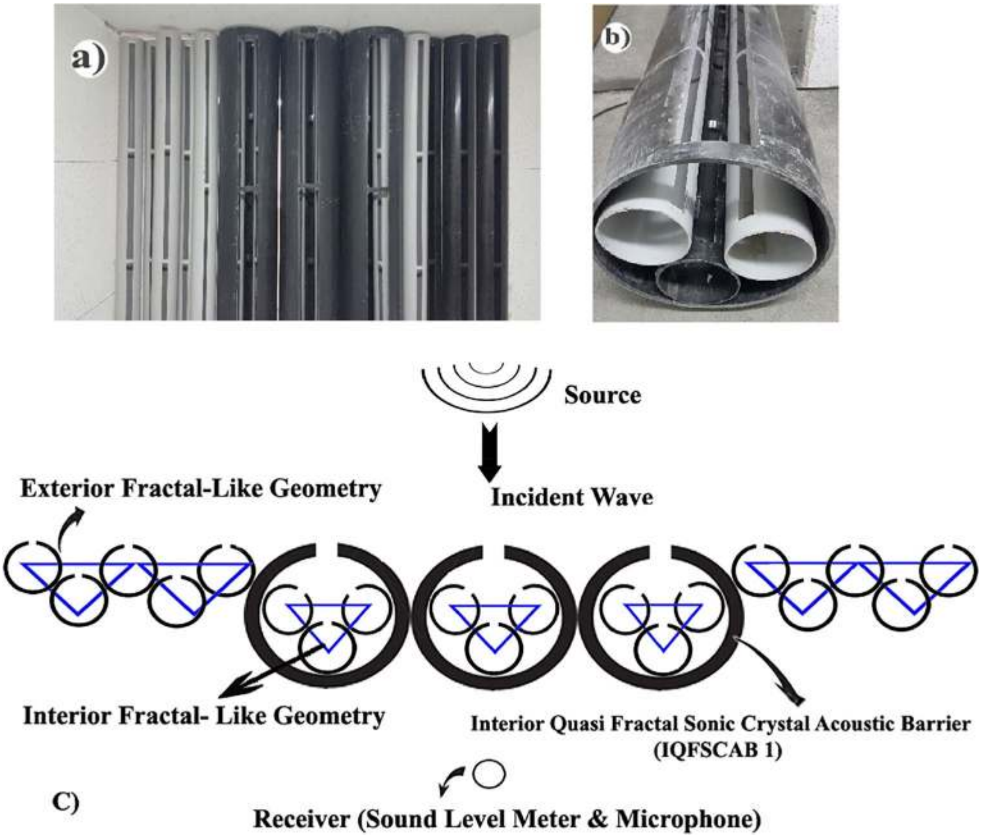


Fig. 12 Show how to set an experimental electronic equipment and microphones and the sound level meter in acoustic room for testing (microphone at a_1 to a_5 position and sound level meter at b position, generator c, electronic record equipment, produce and record results d)

cities of our country. The collection of comprehensive environmental regulations is one of the neglected aspects in the field of noise pollution control in industries and cities in our country. In this regard, it is not surprising to find a creative way for controlling the problem. If the innovative solutions and the results of the noise control researchers do not be considered in the society, the use of personal protective equipment will be inevitable in the daily life and for all the ages. The use of personal protective equipment is ordinary in industrial environments but their using is not tangible and tolerable in the daily life of people.

The goal of introducing a new barrier was solving the problem of three important constraints in the noise control of industries, containing the weight, density and thickness. These factors were considered as important hard parameters on noise control issue. Meanwhile, beauty was also a new concern that has been taken into account by us (see Fig. 19). The low and infra-sound frequency of waves was the same at the stage of

Fig. 13 **a** Acoustic room and barrier set up in the acoustic room. **b** Lateral section **c**) Geometric characteristics and details of designing IQFSACB 1 barrier as interior fractal-like, Schematic shape



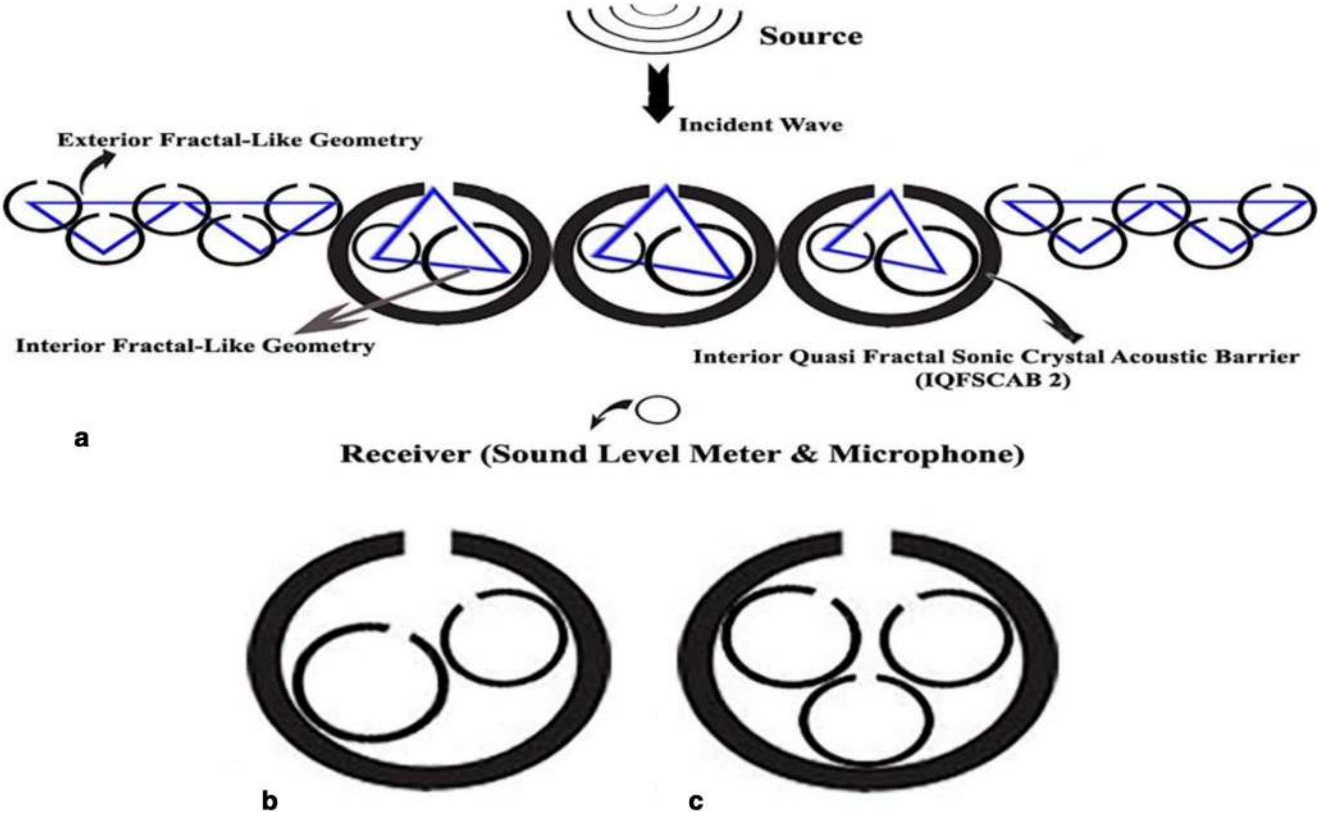


Fig. 14 Characteristics and geometric details of the IQFSACB 1&2 barrier designed as an internal fractal-like. **a** IQFSCAB 2 **b)** Cell design view of IQFSCAB 2 **c)** Cell design view of IQFSCAB 1

the physical propagation process, but the same considerations have been applied to their control. However, shorter wavelength control is easier. In fact, a large concrete wall or a number of complex walls is required to avoid low frequency noise to improve transmission loss. However, most of the walls are inefficient in urban and industrial buildings in the low frequency band. Controlling of noise transmission is a potential problem between the rooms and from the outside to the inside [4, 58, 66].

Results

A large number of arrays tested. The IQFSACB 1 and IQFSACB 2 structures produced with creativity. Figure 17 showed the difference between the IL values and the measurements at the time of testing the IQFSACB 1 and IQFSACB 2 structures. It could be seen that the amount of the reduction of the sound pressure level increased about 28.8 dB in response to the frequencies. The effect of these structures began at a frequency of about 50 Hz and

Fig. 15 **a** Frequency analysis and sound pressure level of pipes with 125 mm diameter inside the acoustic room **b)** Symmetric and Non- symmetric array of pipe in free space **c)** prepared pipe with slit before the tests

Table 1 Specifications of measuring equipment in acoustic room

Class	Range	Model/Type	Device Name	Row
A	0–140 (dB)	BSWA 308	Sound Level Meter	1
–	1800 W	TL-1800	Digital Echo Mixer Amplifier	2
A	3 MHz	PINTEK FG-32	Function Generator	3
A A	60 MHz – 1 G Sa/s 70 MHz – 1 G Sa/s	Tektronix TDS-1002 GwinSTEK GDS-1072A-U	Digital Storage Oscilloscope	4
–	35 Hz-25 KHz	VOX 350	Source	5
Cardioid	20-20 kHz	Jasco 3000-Dynamic	Microphone	6

extended to the range of 1350 Hz. With explained characteristics, the first BG at zero angle caused to occur the wave at IQFSACB 1 at a frequency of 385 Hz and at a IQFSACB 2 at a frequency of 125 Hz. These results were low frequencies and could also be reduced to lower frequencies.

It seemed that the use of absorbent at the exterior surface of the outer pipe may lead to a structure at a higher reduction of the sound pressure level and more moderate frequencies. In nature, there are always objects in which their structures have engineering characteristics (see Fig. 19 and Fig. 20). It means that the nature can be modeled in engineering designs. In pervious scientific texts, exterior fractal geometry was used to control the reflection. One of the creativity made in our study was the use of fractal-like geometry inside the metamaterial. Fractal-like geometry would seem to have a significant effect if this geometry and peripheral structures are repeated. In addition, whatever the number of small internal pipes increases, the lower frequency will be achieved. The cylindrical PVCs have formed a unique internal resonator with the specifications mentioned in the IQFSACB 1 and IQFSACB 2 structures. Figures 16 and 17 represent the IL rate for these internal resonators.

The external core analyzed with an outer diameter of 0.315 m, which produced a resonant peak of about 207 Hz. Although, there were several peaks in these structures, the optimal peak was equal to 185 Hz. It could be seen that the resonance was practically fixed throughout the scattering with the structure of the two sides of the closed pipes.

The use of pipes with different diameters has led to various fluctuations. These fluctuations analyzed using an oscilloscope. The results showed that this structure could reduce the amplitude of the sound and the peak to peak. Fast Fourier Test series (FFTs) results showed that these structures weaken wave and have phase delays (see Fig. 16). The analysis of the data in the sound level meter software also showed this fact. This resonance operation has been able to approximate our frequency to about 50 Hz. The frequency fading threshold appeared at 20 Hz and eventually reached at 50 Hz as you can see in Figs. 16 and 17.

Several resonance peaks observed in this research after new designing of pipes. It seemed that choosing the type of material and its rigidity or elasticity and engineered shapes were effective in this matter.

The Fig. 16 showed that the IL reduced at frequency of 500 Hz just to the amount of 14.4 dB, when the IQFSCAB 1 structure of a non-slit outer pipe in one row was used. When the same structure was used with exterior slit pipes, the reduction reached to 17 dB due to the effect of the outer slit. As matter of fact, when external fractal geometry used with non-slit pipes, the IL was 7 dB. It should point that, at the frequencies below 100 Hz, this external fractal geometry with non-slit pipes did not have much effect. We don't know the exact reason for the discrepancy between our findings and those of other research results.

Table 2 DL_R is the single-number rating of airborne sound insulation performance expressed as a difference of C-weighted sound pressure levels in decibels, according to EN 1793–2 (Lab Test for Airborne Sound Insulation)

Range	Category: Airborne sound Insulation (DL_R)
DL_R = Not determined	B_0
DL_R = < 15	B_1
DL_R = 15 to 24	B_2
DL_R = > 24	B_3

Table 3 Result of new barrier to DL_R

Type of Barrier	Calculated DL_R	Category: Airborne sound Insulation (DL_R)
IQFSCAB 1	15	B_2
IQFSCAB 2	17	B_2

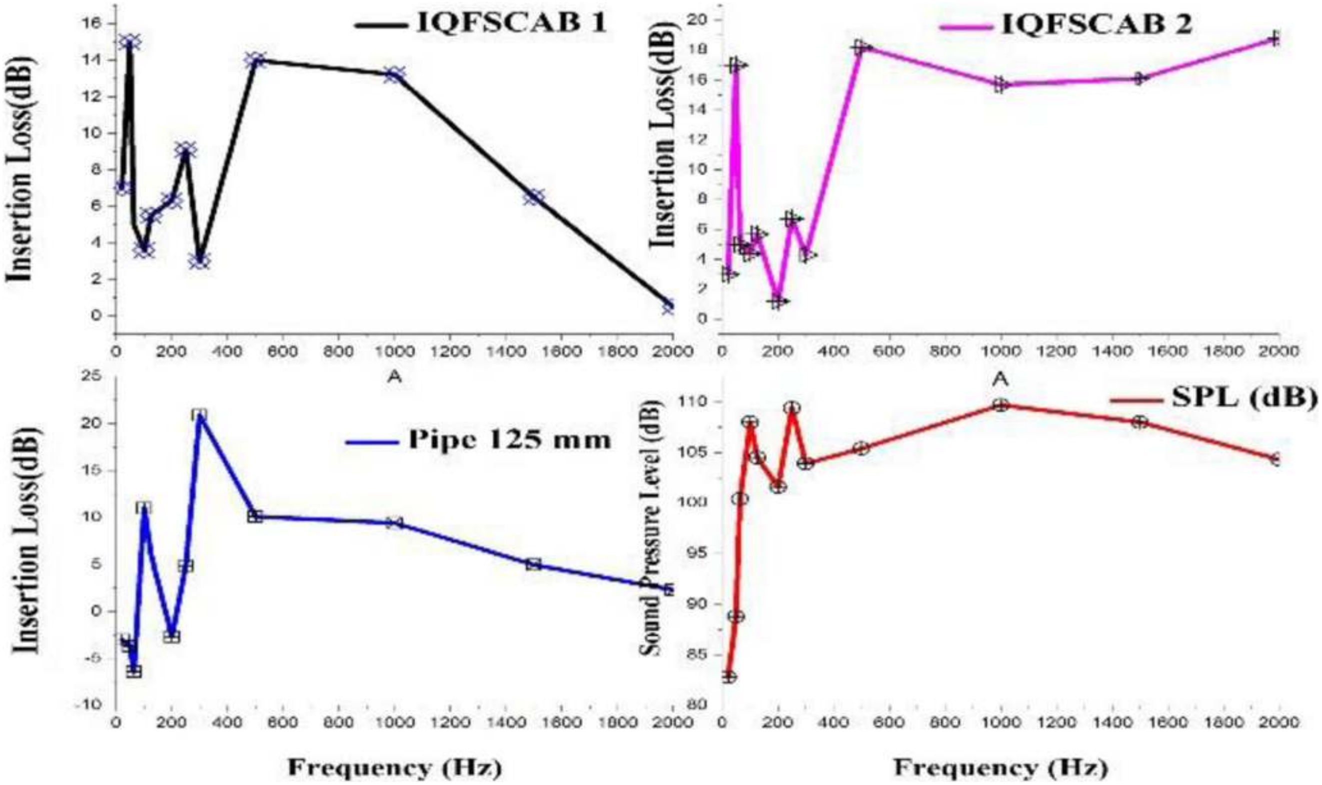


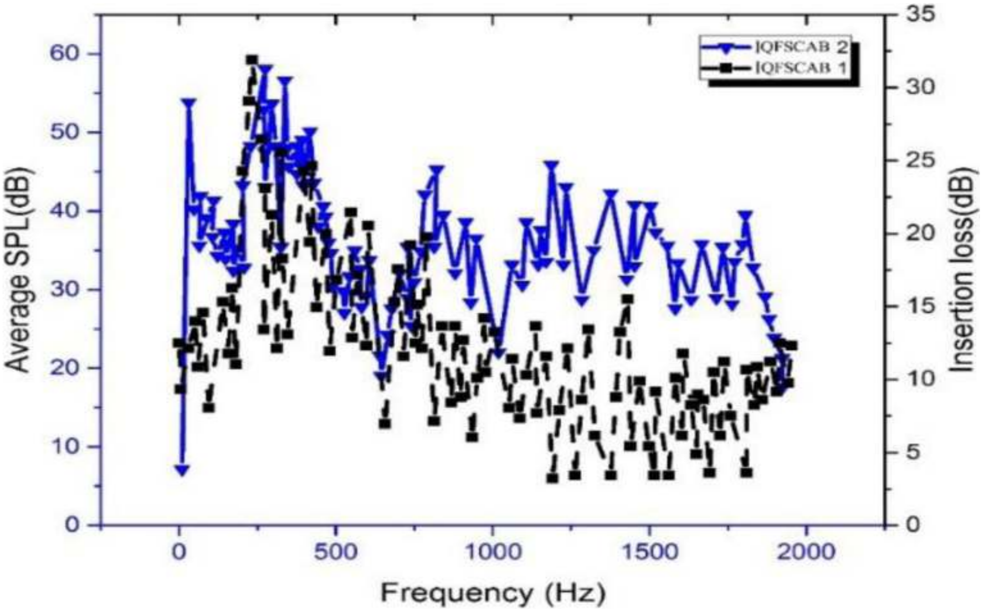
Fig. 16 IL Comparison among three structures, including pipes with 125 mm diameter and IQFSCAB 1 and IQFSCAB 2 as a barrier in the acoustic room, and the bottom right panel: the amount of different sound pressure levels at different frequencies when colliding with acoustic barriers

The effect of sound reduction of the frequency of 700 Hz in IQFSCAB 1 was linearly reduced (see Fig. 17). Another structure that tested was IQFSCAB 2. The difference between in IQFSCAB 1 and IQFSCAB 2 was in the inner pipes. The results showed that great differences in the amount of IL at low frequencies significantly increased. At a frequency of about 50 Hz, the IL was equal to 17.8 dB. In IQFSCAB 2, a linear reduction observed from the frequency 1250 Hz to 5000 Hz.

In IQFSCAB1, the best and most optimal conditions were 315 mm pipe and 100 mm gap, for example, the IQFSCAB 1 structure reduced as following:

- About 15 dB at frequency 50 Hz,

Fig. 17 IL Comparison between two structures, including IQFSCAB 1 and IQFSCAB 2 produced by simulation in COMSOL 5.3a software. In the left vertical axis of the graph, the average sound pressure level in these two structures is observed



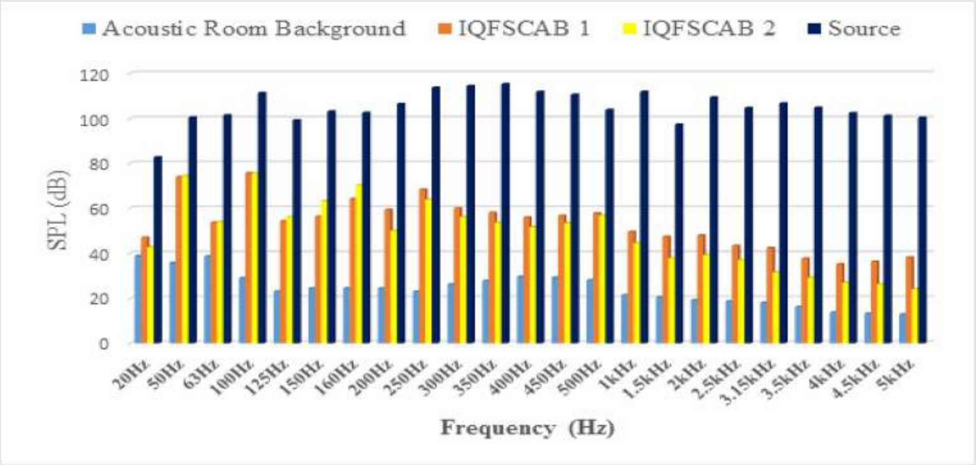


Fig. 18 Comparison of the IQFSCAB 1 (orange) and IQFSCAB 2 (yellow) structures at the time of the frequency analysis of one- third octave band, the sound of the background with blue color, the sound produced by the sound generator marked with black color

- About 9.1 dB within the range of 250 Hz,
- Sound reduction of 13.2 dB at frequency of 1000 Hz.

IQFSCAB1 had a smaller effect at frequencies above 1050 Hz and had a descending chart (see Fig. 16). In this study, the results showed that the IQFSCAB 2 structure would reduce the sound pressure level about 17 dB in the range of 50 Hz (Figs. 18, 19 and 20). Interestingly, IQFSCAB 2 had an ascending effect on the sound reduction in the frequency range above 2500–1050 Hz and this effect reached to 22 dB (see Fig. 16).

Conclusions

In this research, new structures constructed which called the Interior Quasi Fractal Sonic Crystal Acoustic Barrier. IQFSCAB showed a significant acoustic reaction without absorption that was due to repeated resonances and the resulting structure. Three mechanisms were used in IQFSCAB, including resonant phenomenon, BG without absorption mechanism and inner-like fractional structure. The tunability property was tangible based on the internal fractal-like geometry and the pattern inspired from the nature. The increasing of internal reflections and the BG optimization could increase IL. In these structures, the amount of reduction in the sound pressure level will increase significantly if the absorption material uses. Hardness and geometry are very effective at the absorption coefficient of these structures at low frequencies (see Fig. 20).

Technologically, our method had many beneficial applications such as fewer weight, greater beauty, the possibility of color and painting the outer walls. The most remarkable result to emerge from data was that a high-tech design could be considered to the attention of acoustic and sound control specialists in the field of acoustic barriers and as a complement for the classic cases.

A great effort has been made to develop the meta-material function amongst the researchers of the world. The quasi-fractal geometry was developed into the pipes to increase the structural efficiency and reduce the required space by us. Fractal geometry was so far used outside SCAB structures in previous studies. In new meta-material, the density and adsorbent volume regarding thickness and coating surface area were very important. IQFSCAB showed a clear advantage to absorb at frequencies below 100 Hz equal to 15 and 17.8 dB without adsorbent usage. Our study, probably provides additional support for meta-material structures (see Fig. 20).

In this research, IL used and was analyzed by electronic equipment. Index IL measured at several points (see schematic in Fig. 12). The acoustic response of each part

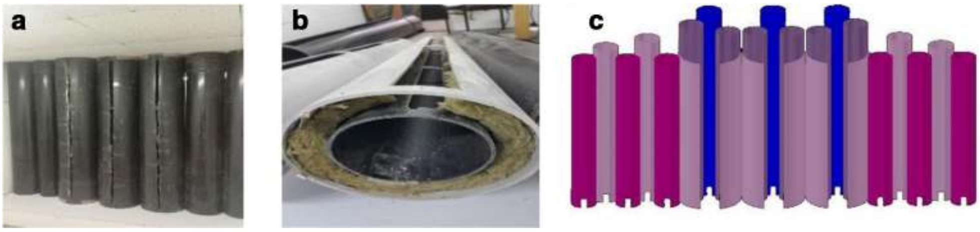


Fig. 19 **a** Shows the examination of a PVC meta-material with 250 mm diameter with interior Rockwool inside the acoustic room, **b** Picture of each part of the scatterer; perforated cover, absorbing cover and inner resonator. Acoustic meta-material with interior Rockwool (internal pipe with 160 mm and external pipe with 250 mm diameter) **c)** Schematic view of IQFSACB from up and in front view with the beautiful-making of internal and external structures (In this figure you see that we can paint the outer and inner surfaces of the pipes like flowers to make them look more beautiful)

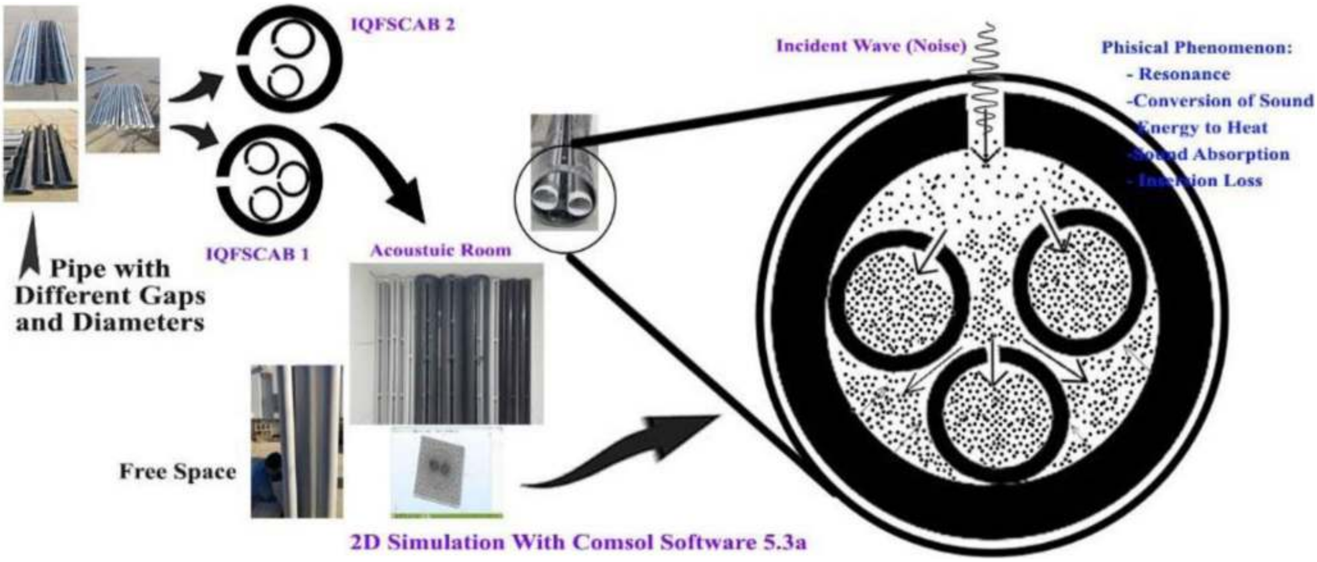


Fig. 20 A schematic summary of the executive steps to produce new barrier of IQFSCAB 1 & 2

of the structure individually analyzed with using an oscilloscope and also one-third octave band weighting network by a sound frequency analyzer to separate the frequency range in which each part operated.

Frequency analysis showed that the observed resonance peak in IQFSCAB 1 was equal to 185 Hz. Results indicated that the change in the gap position had a significant effect on the reduction of the sound pressure level of the frequency. The BG changing in the 125 mm pipes from 10 to 30 mm resulted in 35% sound reduction and placing smaller pipes in a larger pipe than 250 and 315 mm reached to the frequency below 200 Hz. These tests revealed that when the structure of the 125 mm pipes tested solely, it had the greatest effect on increasing the low frequency, and the effect of their reduction observed only in the frequency range of 200–500 Hz. The pipes with 125 mm diameter had insignificant effects at higher frequencies (see Fig. 16). The only use of external fractal geometry was not enough due to Bragg reflections as a controllable physical mechanism, preventing the wave transmission and achieving a high performance of a SCAB.

The most remarkable result to emerge from the data was the use of non-symmetric pipes as meta-material inside of IQFSCAB that reduced the sound pressure level in a wide range of frequencies. Another interesting result was the simultaneous use of external fractal geometry in the form of a gap alongside symmetrical and asymmetric pipes that leads to increase sound reduction. The sound collision angle to the main pipe was changeable between 0 and 30 degrees, and the best effect observed at angle 30 degrees.

An alternative solution is the use of the surveyed materials engineering database [2, 70]. It was found that the changing the materials caused the resonance frequency change in the acoustic crystals (for example: see part a and b in Figs. 3, 4 and Table 4). Further analysis showed that Polyurethane elastomer foam and Rock wool were the optimal materials for absorbing sound waves of low frequencies [67]. In our study, Rock wool has been effective about 6 dB. The designed IQFSCAB 1 and 2 have been able to play a role as a broadband filter which simultaneously have flexibility and determined selective frequency and also allows the use of the system as a device to reduce the sound pressure level of the traffic and industry. We found that a special resonance can be created in the number of special gaps.

Unlike other researches, internal fractal geometry has been used here. The following creative changes were made in our study:

- Internal and external fractal geometry for the resonance and the tunability

Table 4 Characteristics of Rock wool used in the middle pipe of the meta-material

Type	Thickness(mm)	Euro Class	$\lambda\left(\frac{w}{m^0k}\right)$	$R\left({}^{m^2k}/_{w}\right)$	Density ${}^{kg}/_{m^3}$
ISO Blanket Rock wool	50	A$_1$	20 C 0.038	1.32	30

- Two internal pipes with different diameters to increase reduction rate
- External fractal geometry to control the external reflection and use to minimize the reflection rate
- Innovative use of several different gaps to remove various frequencies
- Beautification inspired by the flowers of nature
- Use of lightweight materials with lower executive costs.
- Possibility to use of repeatable fractal-like structures
- Possibility to consider different arrays of pipes
- Creativity in the independence of physical mechanisms in pipes with different diameters.
- Possibility of changing the external color for beautification
- Increasing of resonance in internal pipes.

Here, a new solution is proposed for gaining large band gaps and reducing sounds based on the redistribution of SC elements with regard to internal fractal-like geometry. Previously, this geometry was used only to control the external reflection [52–54, 56]. There was a high tech in resonance frequency in IQFSCAB that could be changed by arranging the array type regarding geometric perspective, the type of pipe diameter and gap type. This was one of the newest and updated solutions of noise control designs in which internal array of flowers in nature is inspiring. The results showed that IQFSCAB without the adsorption process was effective equal to the all other arrays and was able to show a decrease about 17.8 dB at low frequencies (see Figs. 16, 17 and 18). The most important stage was the design method containing the gap change of each set of cylinders for each stage independently.

As can be seen, with the increase in the diameter of the pipe and the increase in the bandgap, the rate of IL in the low frequencies has increased. These results of DOE software showed that the simulations performed in the COMSOL 5.3a software as well as the experimental results obtained in the acoustic room are highly accurate (see Figs. 8 and 9). Under these conditions, it is legitimate to pose a new perspective on SC.

Important technical issues and economic factors in designing new barriers should be considered such as costs, executive issues, engineering, aesthetic effects and effects on the environment by designers and specialists. It could be concluded that, the results were consistent with repeated experiments and showed good agreement. In fact, each pipe's array executed several times with the best solutions such as best diameter and BG. We used the oscilloscope to validate the results of experimental experiment. It was concluded that the measured results were satisfactory and valid. The survey of the results of wave analysis and measurement devices has shown a good agreement with the results of laboratory experiments and the results of previous studies. The research results have appeared the validity of this new models. These results have suggested that this is a very important finding.

It seems that the use of special equipment such as an anechoic chamber and omnidirectional microphones and other absorbent materials can be of great help in improving our results. Future work will be devoted to investigating these three alternative possibilities.

Although, the more accuracy does in acoustic designs, the problems often occur during installation. We need the accurate monitoring at the site during construction and installation process. Technical instructions were required at the time of installation. Indeed, practical and functional aspects of the barrier should be highlighted in the design characteristics. With using these innovative barriers, the concern of the owners of the industry and acoustic designers will decrease. Meta-materials are a new feature for noise control. Meta-materials are practically interesting for environmental scientists. Historically, no protective or compensatory legislation has been existed for people who are exposed to noise in Iran and the industries does not have the necessary trust to designers and noise pollution control specialists. In other words, cultural activities seem necessary, such as a conscious presentation of the advantages of noise control, the effectiveness of long-term barriers, offering ways to increase trust to acoustic specialists.

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Compliance with ethical standards

Conflict of interest The authors confirm no conflicts of interest associated with this publication.

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