Acoustic applications of metamaterials

Gino Iannace [1,*,†], Giovanni Amadasi [2,†], Franz Policardi [3,†], and Amelia Trematerra [4,†]

[1] *Università della Campania Luigi Vanvitelli, 81031 Aversa, Italy*
[2] *SCS-ControlSys - Vibro-Acoustic, Padova, Italy*
[3] *University of Ljubljana, Faculty of Electrotechnical Engineering, Ljubljana, Slovenia*
[4] *Università della Campania Luigi Vanvitelli, 81031 Aversa, Italy*

Abstract
Acoustic metamaterials (AM) is a recent topic, as first specific studies were carried out in the fields of optics and electromagnetism and only in recent years have metamaterials (M) been developed in the field of noise control. This paper presents some 1D, 2D and 3D simple geometric structures and discusses their acoustic theory. Furthermore, applications as AM considering 2-dimensional structures made by cylindrical elements and 3-dimensional structures made by spheres are investigated. In the analyzed configurations, a sound attenuation in the frequency domain was noted between 1.000 Hz and 10.000 Hz. These first results show that M structures specific arrangements can be applied for acoustic filters noise reduction from air ventilation systems up to noise barriers for road applications. Metamaterials can be used for the acoustic correction of monumental environments, in those places where the conservation of aesthetics takes on fundamental value. For example, metamaterials can be new elements of urban furniture to protect the cultural heritage. Further developments could be the applications with machine learning techniques to optimize the lattice structures to improve the effectiveness of metamaterials.

Keywords
Metamaterials, acoustics measurements, frequency, insertion loss, spheres, attenuation

1. Introduction

As far as we know, the first applications and studies on geometrically repetitive structures were carried out in the field of optics and subsequently on electromagnetism. Historically speaking, the creation of a strange material (today called "metamaterial" (M)) dates back to the Roman's era "Lycurgus cup" around 4th century A.C.

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* Corresponding author.
† These authors contributed equally.
gino.iannace@unicampania.it (G. Iannace)
0000-0003-3182-3934 (G. Iannace)

The Lycurgus cup shows different colors depending on the way the light passes through it: green when illuminated from the front, while the non-illuminated side is red. The particular effect was obtained by inserting small gold and silver elements into the glass. The colorfully stained-glass windows of Northern Europe medieval gothic churches are elements made with optical M structures too. In modern times, a practical application of M can be found during World War II, when German submarines were covered with rubber elements with holes at a regular pitch, typical of the Helmholtz resonance systems, in order not to be detected by English ships sonars. This arrangement was called Alberich, referring to the name of a warrior who fought wearing an invisible cloak. Today, modern submarines and stealth airplanes have external surfaces covered with M structures too for the same reason. In underwater acoustics these high sound attenuation elements are used to cover platforms surfaces in water in order to limit the harmful effects of industrial processing noises on maritime fauna. The brilliant theoretical idea of both electric and magnetic negative materials permittivity ε and μ was developed by V. G. Veselago and published in Russian in 1967 and in English in 1968; the theory hypothesize a material which, when hit by an electromagnetic wave, did not resist the propagation of the wave, allowing it to pass on the external surface without generating reflections. The material should have had a negative refractive index. At that time, the theory did not gain much traction but later this idea was applied by J. B. Pendry's research in 1995 in order to design optical lenses with low refraction and improving vision. In 1999, Prof. R. Walser (University of Texas) was the first to adopt the name “Metamaterials” (M) as new materials composed of periodic cell structures not existing in nature; today’s research on M applications extends from buildings defense against the action of earthquakes to heat transmission phenomena and to applied acoustics. It is well known that noise control and mitigation improve quality of life and in recent decades many governments adopted laws requiring noise reduction solutions, so only in recent years have some Acoustic Metamaterials (AM) been introduced to control noise propagation, representing a new applied acoustics sector. The present work reports the acoustic applications of some geometric structures creating M; after a brief theoretical explanation and some applied examples, 2-dimensional (2D) structures made with cylindrical elements and 3D structures made with specifically arranged spheres are considered. In the analyzed configurations, a sound attenuation in the frequency domain between 1.000 Hz and 10.000 Hz was noted. These results allow us to conclude that structures made with M can be applied to develop acoustic filters for the reduction of noise from air ventilation systems up to noise barriers for road applications. Metamaterials can be used for the acoustic correction of monumental environments, in those places where the conservation of aesthetics takes on fundamental value. For example, metamaterials can be new elements of urban furniture to protect the cultural heritage.

2. Theory

Wave propagation control depends on the interaction between incident waves and the elements they pass through. When these elements are arranged according to a regular geometry, they create a periodic structure allowing incident waves attenuation through destructive interference. M structures can be classified into three regular geometries.

Figure 1 shows: A the 1-dimensional (D) structure with flat elements, characterized by a single periodic direction, B the 2D structure referring to cylindrical elements, characterized by 2 periodic directions and C the 3D structure referring to spherical elements, characterized by 3 periodic directions.

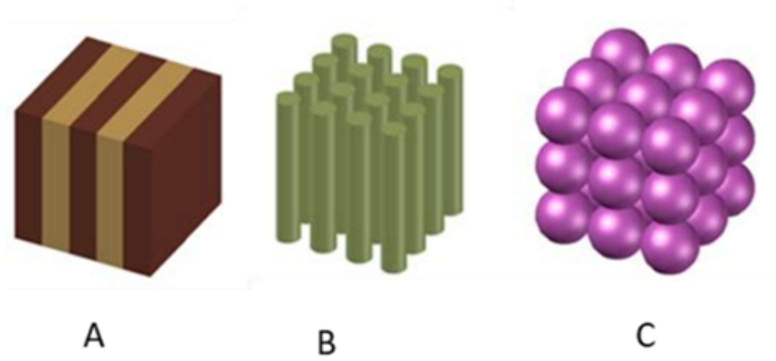


Figure 1 : Metamaterial (M) elements structures: A 1D, B 2D, C 3D.

Destructive interference attenuation occurs at the frequency at which the wavelength is comparable to elements size and reciprocal distance. This concept is expressed by Bragg's law, which evaluates the wave attenuation passing through a grating at a specific frequency. Solid elements disposed in a periodic structure attenuate energy by the destructive interference sound waves generate when passing through the structure. The band gap frequency (f_{BG}) depends on the incident angle of the wave, the lattice constant (α) and the sound speed in the specific medium (c) respectively, as summarized in the following equation:

$$f_{\_BG} = c/2a$$

On this basis, when a plane wave affects elements arranged within a regular geometry structure, the distance between the wave fronts can be described as a sin(ϕ), where *(ϕ)* is the plane wave incidence angle, *a* is the distance between two solid elements consecutive rows and *λ* is the incident wave wavelength. The destructive interference condition is that λ / 2 = a sin (ϕ). Figure 2 shows the theoretical plane sound wave scattering when hitting a 2 solid elements rows barrier [1-8].

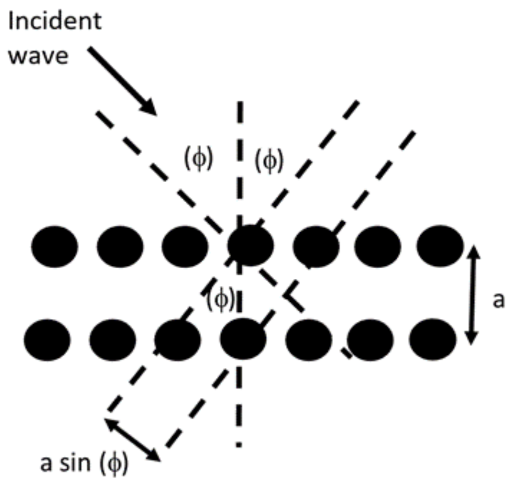


Figure 2: Plane sound waves scattering phenomenon across a 2-row cylindrical solid elements array.

3. Metamaterials for acoustic applications

One of the first AM applications was the so called "Órgano" sculpture created by the Spanish artist E. J. Sempere: the moving sculpture is exhibited in Madrid since 1977 and is based on a minimalist design simple geometry consisting of 30 mm diameter steel bars arranged according to a 2D square lattice, with a pitch of 100 mm. Later (1995) acoustic measurements highlighted sound attenuation at frequencies between 1.000 Hz and 5.000 Hz. The Órgano sculpture is considered the first artistical experimental example of a 2D M periodic structure, as shown in Figure 3.

Figure 3: Sculpture «Órgano» by Eusebio Juan Sempere, Madrid 1977.

Some authors tried to apply M for noise control inside dwellings: the aim was to create a so called "Helmholtz resonant meta-house" with transparent cylinders arranged in a constant-pitch circular grid. The six cylinder lines were hollow and had vertical slots to increase resonance effects, as showed in Figure 4. The authors made a 1:10 scale model and verified a sound attenuation of about 10 dB in the range 1.000 Hz - 10.000 Hz. If this experiment will show comparable acoustic behavior in real 1:1 scale, its realization may expand noise propagation control within dwellings, when acoustic comfort special conditions are required.

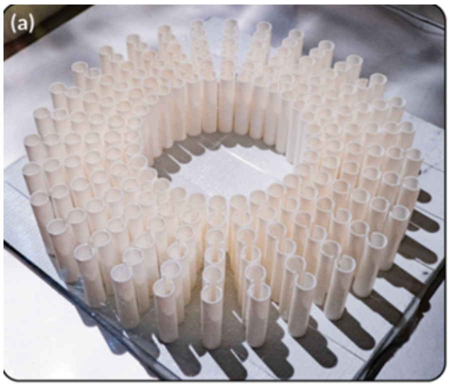


Figure 4: Meta-house 1:10 scale model.

Other authors proposed M systems as acoustic barriers. Acoustic barriers are used to reduce the noise propagation effects emitted by means of transport and can be used to limit noise emitted by construction works. Traditional acoustic barriers are realized using a sound-absorbing material layers inside sheet metal panels. The sheet metal major surface facing the noise source is perforated so that the incident energetic noise waves can be absorbed by the sound dumping material and not sent back or transmitted. Noise attenuation is mainly determined by the barrier height, as noise is transmitted beyond the barrier due to the diffraction effect [9-13]. Traditional acoustic barriers are solid long elements and have a negative visual impact from an aesthetic point of view. The metamaterials can be new elements of urban furniture to protect the cultural heritage. Many authors have reported acoustic measurements on M acoustic barriers application effects. Several studies investigated cylindrical bars arranged in a 2D M regular manner and Figure 5 shows a wooden M (1: 10) scale model barrier composed by 5 of 15 mm diameter elements at a 40 mm distance.

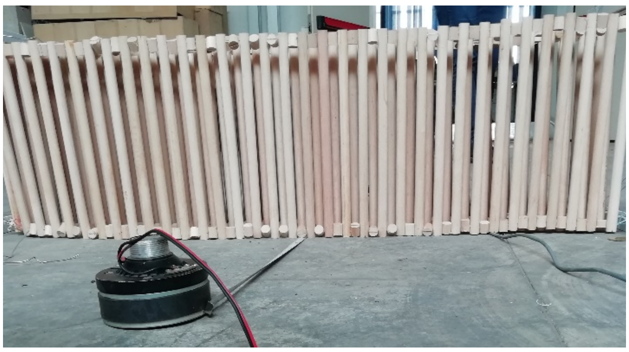


Figure 5. Wooden M 1: 10 scale model barrier composed by 15 mm diameter elements.

Wooden M noise barrier acoustic 1/3 octave mid-high bandwidth noise attenuation measurements between 1.000 Hz and 10.000 Hz show that the insertion loss value reaches a sound attenuation of at least 6 dB between 3.150 Hz and 10.000 Hz with a peak of around 10 dB in the 4.000 Hz - 8.000 Hz frequency range, as shown in Figure 6 [14-19].

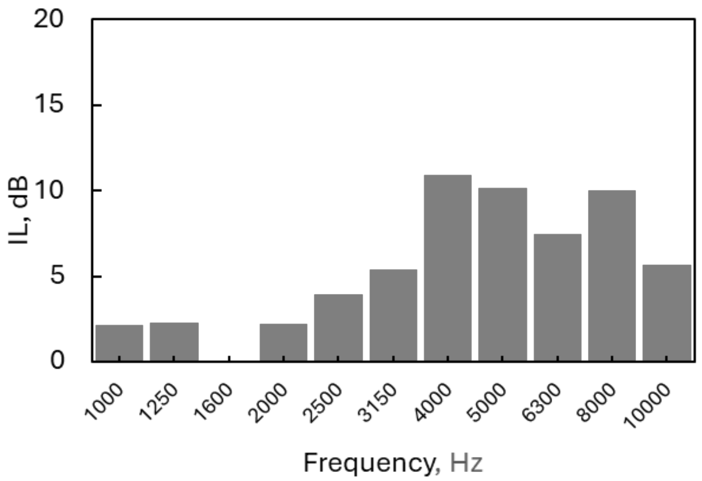
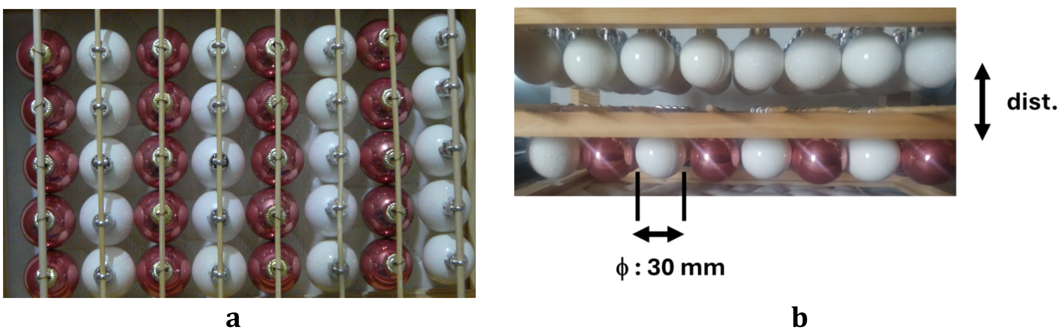


Figure 6. Wooden M (1: 10) scale model barrier 1/3 octaves insertion loss acoustic measurements.

4. 3D M structures sound attenuation

This paragraph presents three different 3D M structures made with spheres sound attenuation measurements. The polymer 1.200 kg/m^3 density 30 mm diameter spheres are used to create a 3D meta surface in order to control noise attenuation. The horizontal and vertical spheres 3D structure constant space pitch distribution and dimensional layout are shown in figure 7 (a) and (b).



Figures 7 (a) and (b): (a) Horizontal and vertical spheres 3D structure constant space pitch distribution, (b) dimensional layout

Acoustic measurements were carried out placing a sound source (RCF TW50) in a box, while the upper side was open. The box containing the sound source had rigid and fixed walls in order to limit unwanted vibrations and was covered with sound-absorbing material so that the preferential sound emission direction was upwards. The measurement microphone was placed at a 0.5 m distance from the opening connected to an acquisition A/D card (CLIO) generating a sine sweep signal, as shown in Figure 8 [20-22].

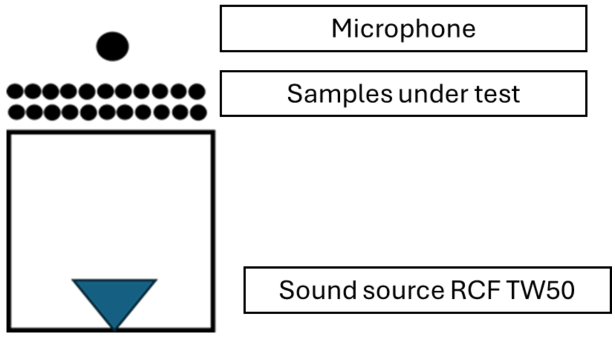


Figure 8: Measurement set-up

Measurements were performed first with free mouth box and subsequently covered with three different 3D structured M made of 30 mm diameter spheres structures. The measured data have been analyzed in 1/3 octave frequency bands between 800 Hz and 10.000 Hz and are reported in terms of IL (insertion loss) or as the difference between the sound level measured without M and the sound level measured with the M under test; the sound attenuation is obtained as the difference between the level measured without samples (LR without) and with the provision of samples (LR with), summarized in equation:

IL = LR without – LR with (dB).

The analyzed and compared configurations were the following:
A) single 30 mm diameter spheres row,
B) double 30 mm diameter spheres row placed at 20 mm distance,
C) double 30 mm diameter spheres row placed at 40 mm distance.

In configuration A, i. e. single 30 mm diameter spheres row, the M configuration has an even effect on sound attenuation: 2 dB in almost all 1/3 octave bandwidths, increase of another 1 dB between 2.000 Hz and 6.300 Hz, with a single clear attenuation peak of 5 dB around 3.150 Hz, as shown in Figure 9.

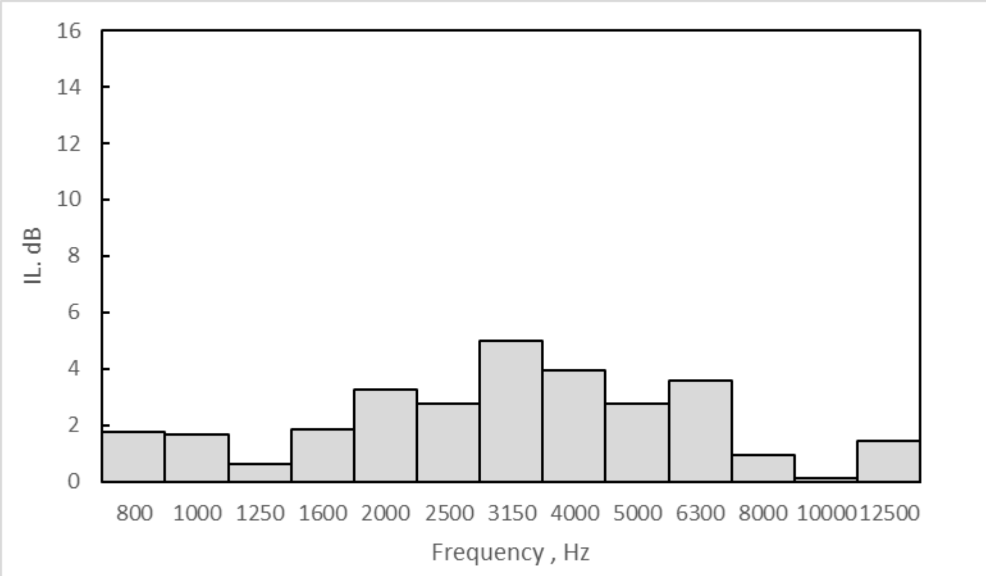


Figure 9: Single 30 mm diameter spheres row.

In configuration B, i. e. double 30 mm diameter spheres row, placed at a 20 mm distance, the M configuration has a sound attenuation: all 1/3 octave bands between 800 Hz and 10.000 Hz at least 1 dB. Between 800 Hz and 6.300 Hz with an attenuation of 6.5 dB at 800 Hz, and an attenuation of 7 dB at 3.150 Hz; an attenuation of almost 10 dB around 6.300 Hz [23-24]. The two higher frequency bands between 8.000 Hz and 10.000 Hz are lower their attenuation coefficient at just 1 dB, as shown in Figure 10.

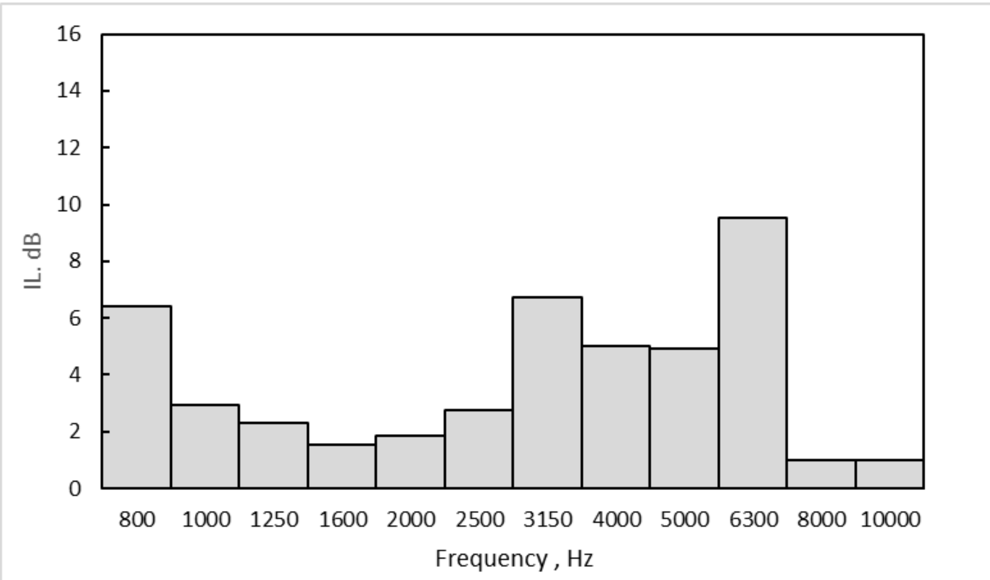


Figure 10: Double 30 mm diameter spheres row, placed at a 20 mm distance

In configuration C, i. e. double 30 mm diameter spheres row placed at a 40 mm distance, the M configuration has another completely different effect on sound attenuation: almost all 1/3 octave bands between 800 Hz and 12.500 Hz show different attenuation indexes ranging from 0 dB between 5.000 Hz and 6.300 Hz up to 1 dB between 1.250 Hz and 1.600 Hz, 1,5 dB at 3.150 Hz, around 2 dB at 1.000Hz and 8.000 Hz, 3 dB at 800 Hz and 12.500 Hz, 5 dB at 2.500 Hz, 6 dB at 4.000 Hz, 7 dB at 10.000 Hz and 12 dB around 2.000 Hz, as shown in Figure 11.

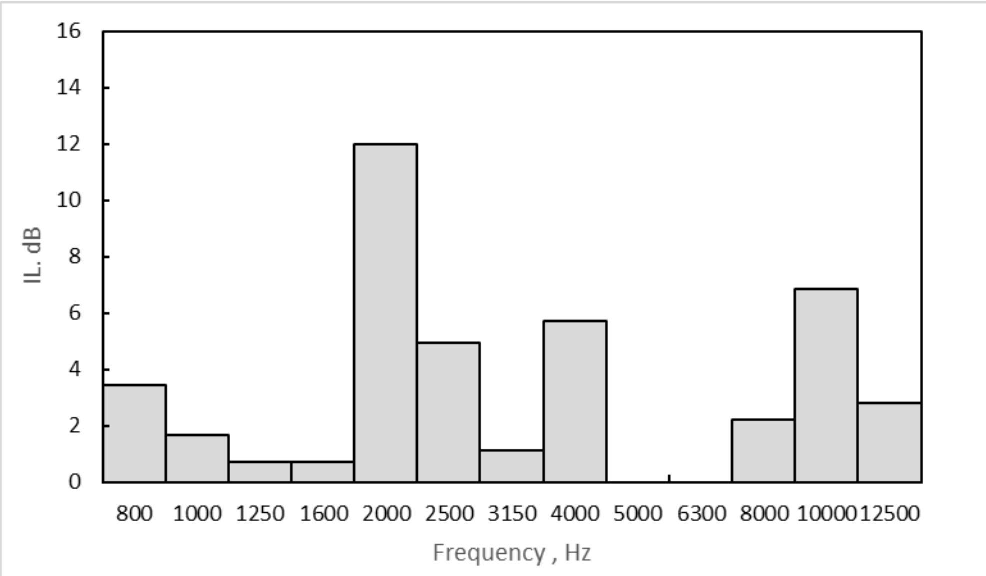


Figure 11: Double 30 mm diameter spheres row, placed at a 40 mm distance

5. Discussion

Present work presents, after a brief historical and a theoretical discussion, some existing 2D and 3D M arrangements scale experiments and their results. We then propose, realize and measure sound behavior of 3 specific M structures composed by little polymer spheres arranged according to a 3D lattice. Acoustic measurements were caried out with a sine sweep technique and 1/3 octave band graphic results representation clearly shows that our proposed M structures present the sound attenuation in different frequency ranges. Single row AM disposition shows an even energy attenuation from 800 Hz up to 12.500 Hz between 0 dB and 5 dB. Double row first AM disposition show a pronounced U behavior between 800 Hz and 6.300 Hz from the 6.5 dB at 800 Hz to 1.5 dB at 1.600 Hz rising up to – 7 dB at 3.150 Hz and 10 dB at 6.300 Hz. Double row second AM disposition show a more chaotic sound absorption behavior with 0 dB attenuation at 5.000 Hz and 6.300 Hz up to an astonishing 12 dB energy attenuation at 2.000 Hz, without a clear tendency characteristic. So different energy reduction behaviors in sound attenuation open many practical possibilities, as they can be specifically adapted for different purposes and "tuned" as noise filters from air ventilation systems up to noise barriers for road applications [25-29].

6. Conclusions and Future work

Due to the demonstrated different AM attenuation capability of our arrangements, we aim to extend our work repeating the experiments with a broader frequency sine sweep, in order to investigate infrasound, sound and ultrasound acoustic behavior of these specific arrangements. It would be probably interesting to investigate the acoustic behavior of this specific arrangement and model from very low frequencies to at least 10.000 Hz. Further development of this acoustic application will measure hollow spheres in order to obtain resonant systems. Metamaterials can be used for the acoustic correction of monumental places, where the conservation of aesthetics takes on fundamental value. For example, metamaterials can be new elements of urban furniture to protect the cultural heritage; it is no coincidence that a sculpture is one of the first examples of the applications of metamaterials. Further developments could be the applications with machine learning techniques to optimize the lattice structures to improve the effectiveness of metamaterials.

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