INTERNATIONAL JOURNAL
OF
CONSERVATION SCIENCE

ISSN: 2067-533X Volume xx, Issue xx, July-September: 805-810 www.ijcs.uaic.ro

MONUMENTS PROTECTION AGAINST VIBRATIONS AND NOISE USING QUASI ONE-DIMENSIONAL ACOUSTIC BARRIERS

Wojciech SOCHACKI[1], Katarzyna BLOCH[2], Sebastian GARUS[3,*]

[1] Department of Mechanics and Fundamentals of Machinery Design, Czestochowa University of Technology, ul. Dąbrowskiego 73, 42-201 Częstochowa, Poland
[2] Institute of Physics, Faculty of Production Engineering and Materials Technology, Czestochowa University of Technology, 19 Armii Krajowej, 42-200 Częstochowa, Poland
[3] Department of Mechanics and Fundamentals of Machinery Design, Czestochowa University of Technology, ul. Dąbrowskiego 73, 42-201 Częstochowa, Poland

---

Abstract

Continuous industrial development also entails negative effects such as increasing the intensity of road traffic or the use of more efficient but louder and vibration-producing industrial equipment. This generates high-intensity acoustic waves, which, apart from adverse effects on people, cause vibrations in historic architectural structures that can propagate throughout the building and affect exhibits. Strictly defined vibration frequencies even at low intensity can lead to resonance phenomena and destruction of the object. Modern phononic crystals, due to the occurrence of the phononic bandgaps phenomena (waves with given frequencies do not propagate in the structure) allow to eliminate unfavorable frequencies and to significantly reduce the energy carried by mechanical waves. The use of a genetic algorithm along with the transfer matrix method with a properly selected objective function proposed in the article allows for the design of quasi-one-dimensional structures allowing the construction of acoustic barriers with optimal properties that allow protection against mechanical waves of high intensity of particularly valuable places. As an example, the design of transparent 10, 15 and 20-layer barriers made of glass and PVC is shown. A significant reduction in the sound pressure level for the acoustic frequency range has been demonstrated.

Keywords: *Vibration protection; Noise barriers; Transfer matrix; Genetic algorithm; Mechanical wave propagation*

Introduction

Noise is considered an important factor in public health. It is a common cause of irritation for people exposed to its effects. Noise affects the general state of human health [1]. In particular, noise can be a source of stress and lack of concentration. It may also affect sleep disturbances and cause cardiovascular changes, and may exacerbate other previous physiological disorders. However, noise has an impact not only on humans, but also on objects in which man resides and objects in the human environment. Thus, historic objects that are particularly important for us are also exposed to noise and as a result also to vibrations.

When considering the issue of protection against noise of historic buildings, it is necessary to take into account both the impact of noise on the facade of such objects as well as the impact on people who stay in such objects. The first case occurs when an acoustic impact on the facade causes its vibrations. Research on such an issue was presented by *A.T. Lloret et. al*

---

[*] Corresponding author: gari.sg@gmail.com

[2]. The authors analyzed the impact of the vibroacoustic factor on the vibrations of a historic building. In the second case, the acoustic impact on the building is analyzed in terms of the well-being of the people who stay in it. Hence, research is more focused on the insulating properties of flats [3]. Still other works include studies on sound insulation of building facades [4, 5]. The authors examined to what extent the facade material attenuates noise depending on the frequency of the noise source.

To protect against noise, it can be place acoustic screens along roads, bypasses, highways or railways to separate noise sources from the exposed environment. Most of these barriers have a limited acoustic effect due to the reduced geometric shadow zone behind the barrier produced by the diffraction of acoustic waves on the upper edge of the barrier [6]. In addition, acoustic screens of this type are usually continuous walls with a negative impact on the landscape. They are impermeable to sunlight and provide considerable resistance to airflow.

Acoustic barriers based on phononic crystals (PnC) are completely different barriers. Research on phononic crystals began intensively at the end of the 20th century [7-9]. One of the first works on acoustic barriers research was work [10]. In this work have been examined how the perception of auditory distance is modified for a particular sound field: the transmitted field of an acoustic source through a phononic crystal slab. An interesting analysis of the sound wave propagation through the phononic barrier in field conditions is presented in [11]. In this work, Sanchez-Perez et al. presented the results of outdoor experiments for two-dimensional audio structures, from which it can be concluded that these structures are appropriate devices for reducing noise under free field conditions. Carried out in [12] the perceptual analysis shows that a noise barrier made of a PnC is able to attenuate the loudness of a noise source in the band gaps in the same level as a usual free-standing noise barrier.

An interesting property of the PnC acoustic barrier is the ability to suppress specific frequencies in the spectrum of noise (due to destructive interference) propagating through the barrier. This opens the possibility of protecting monuments also by eliminating from the spectrum noise frequencies that could become the cause of their resonance vibrations.

Methods, results and discussion

The work analyzes acoustic barriers surrounded by air at a temperature of 20 degrees Celsius with a mass density of 1.21kg/m^3 and a sound velocity of 343m/s [13]. The structures consisted of lossless layers of glass (material A – mass density 3880kg/m^3 and sound phase velocity 4000m/s [14]) and PVC (material B – mass density 66kg/m^3 and sound phase velocity 913m/s [13]) each 1.0cm thick. Transparent materials with significantly different material parameters were used to build the structure. This selection of layers causes a large difference in acoustic impedance, which significantly increases the reflectance between the layers. The sound source intensity was assumed to be 90dB and the reference pressure value was $2\cdot10^{-5}$Pa. The propagation of mechanical wave in the structure was analyzed using the transfer matrix method, while the optimization of the structure was performed using a genetic algorithm.

The transmition of an acoustic wave propagated through a quasi one-dimensional acoustic structure built of many layers was investigated using the transfer matrix method (TMM). This is a general method for predicting transmission and reflection coefficient in multilayer structures. This method was successfully used in [15-20]. The authors *O. Dazel et al* [15] presented a general way of determining the acoustic reflection coefficients and transmission coefficients of multilayer panels. The TMM algorithm was used by *S. Garus and W. Sochacki* [16] to study the power spectrum and phononic properties of Severin's quasi-one-dimensional aperiodic structure. The issue of sound wave propagation in a one-dimensional water channel containing many air blocks was investigated (using TMM) by *P.G. Luan and Z. Ye* [17]. Similarly, *M.M. Sigalas and C.M. Soukoulis*s [18] studied the propagation of elastic waves in multilayer structures made of two different materials using the TMM method. The analysis of three types of multilayer structures (binary-periodic, quasiperiodic and aperiodic) with a defect in the form of a piezoelectric layer was carried out by *S. Garus et al* [19] using TMM. In paper *L. Han et al* [20] proposed a modified MTM transfer method for calculating the elastic vibrations of Euler beams as phononic crystals. In this work, the Transfer Matrix Method was used to investigate the possibility of noise suppression by an acoustic barrier based on phononic crystals.

The matrix transmission method used in the article was described in *S. Garus et al* [21]. The mechanical wave transmission through the structure is determined as the square of the absolute value of the inverse of the first word of the diagonal of the characteristic matrix. This matrix consists of the products of the mechanical wave propagation matrix in a given layer (it is affected by the thickness of the layer and the phase speed of sound propagation) and the transmission matrix at the layers boundary (determined by the transmission and reflectance coefficients of given layers and the acoustic impedance of the materials).

A genetic algorithm was used to optimize the distribution of layers in the structure. It involves minimizing the objective function, which was defined as the product of the normalized transmission integral (to reduce propagated energy) and normalized integral of the absolute value of the transmission functions derivative (to eliminate high transmission peaks with a small half width) in a given frequency range. In order to compare structures between populations, the value of the objective function without normalization should be determined. In order to eliminate the mechanical waves eigenfrequencies in order to protect monuments against harmful resonance phenomena, a weighted average with a correspondingly higher weight w_f for the range around the resonance frequency and with a weight of $1\text{-}w_f$ for the whole range of acoustic frequencies (up to 20kHz) should be used as a objective function.

After the initialization of the simulation space, the first population of 20 structures was generated. The value of the objective function was determined for each of random structures and then the population was sorted according to it. The two structures with the most favorable target function value are transferred to the next population without mixing genomes. The last two are removed from the population and random structures are selected in their place, this procedure, like the 1% chance of mutation of each population gene, aims to reduce the chance of simulation getting stuck in a minimum of local solutions space. Then the other structures are mixed in pairs. Multilayer systems were tested for the number of layers of 10 (Fig. 1), 15 (Fig. 2) and 20 (Fig. 3).

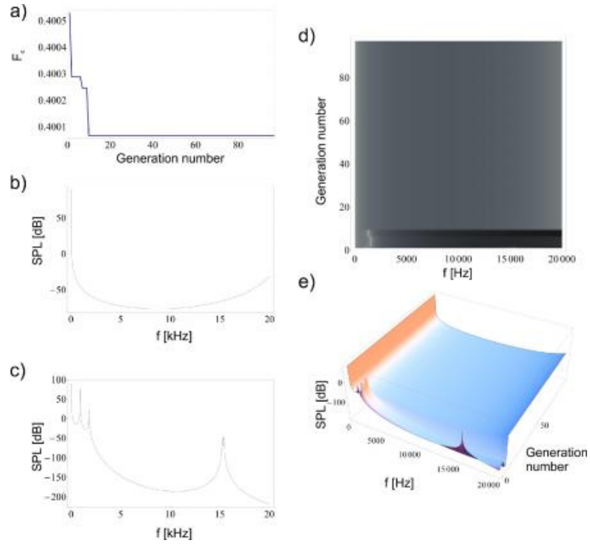

Fig. 1. Results of 10-layer structure analysis.

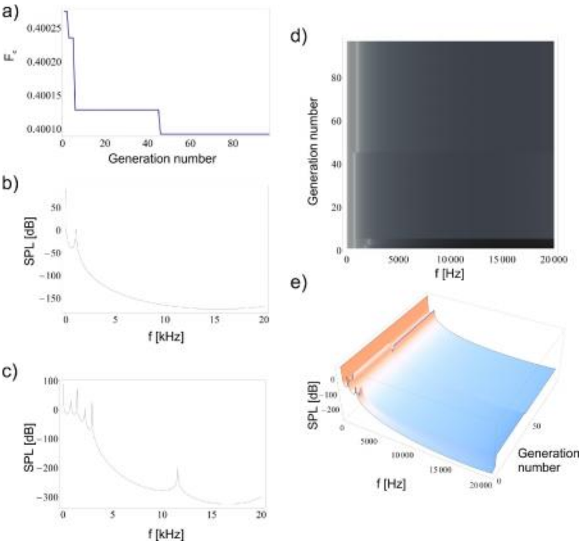

Fig. 2. Results of 15-layer structure analysis.

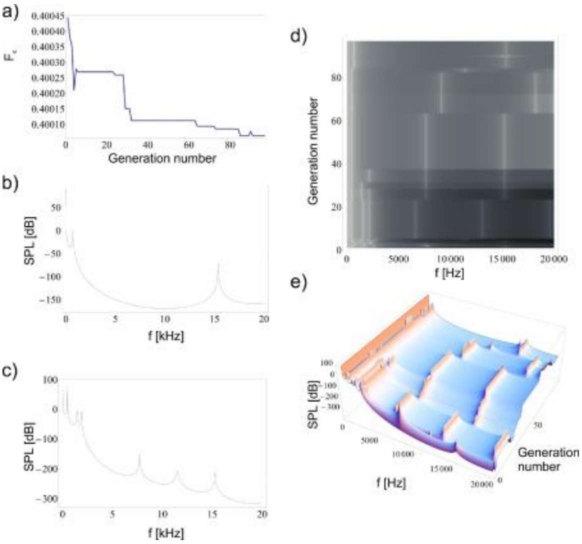

Fig. 3. Results of 20-layer structure analysis.

Preliminary analysis showed that a stable simulation result of less than 100 iterations of the genetic algorithm was achieved.

Figures 1a, 2a and 3a respectively show the objective function values for the best individuals in each population for 10, 15 and 20 layered structures. As the state space increases, the amount of population necessary to find the optimal solution increases, although the percentage of space searched decreases significantly as shown in Table 1. Figures 1b, 2b and 3b show Sound Pressure Level (SPL) as a function of frequency for the best structures, and Figures 1c, 2c and 3c respectively the worst structures from the searched space of solutions for different numbers of layers. The found structures are summarized in Table 1 together with the values of the objective function.

Table 1. The best and worst structures of the searched space of solution states for different amounts of layers.

The number of layers	Analyzed solution space	Tested structures before finding solutions	Analyzed structure		Objective function value
10	2^{10}	200 (19.5 %)	Best	A_9B_1	4000.67
			Worst	$A_1B_3A_1B_3A_2$	5005.59
15	2^{15}	920 (2.8 %)	Best	$A_6B_1A_8$	4000.61
			Worst	$A_1B_4A_1B_2A_1B_2A_1B_1A_1B_1$	4693.74
20	2^{20}	1820 (0.17 %)	Best	A5B5A10	4000.54
			Worst	$B_2A_2B_1A_3B_2A_1B_6A_3$	6060.99

Figures 1d, 2d, 3d and 1e, 2e, 3e show respectively density plot and 3D plot with SPL values in the frequency function for the best individuals for each generation. The evolution of the best structures in each population can be traced to the optimal solutions found. It can be seen that the increase in the number of layers affects the appearance of transmission peaks with a small half width.

Conclusions

The probabilistic nature of the genetic algorithm allows finding the best possible solution for a partial search of the space of all possible structures. Considering the three types of 10, 15 and 20-layer structures constructed of lossless and transparent glass and PVC materials, it was shown that the properties of the acoustic barrier were slightly improved, indicating that the use of real materials exhibiting mechanical wave absorption would significantly improve the properties of the structure with more layers. All the optimal solutions found were characterized by a high value of the reflectance coefficient and low transmission, which means that they can be used as acoustic barriers to protect against the energy of undesirable mechanical waves in places of particularly valuable (such as around museums, monuments, monuments of culture and nature) allowing to protect people and exhibits. It should be noted that the algorithms used allow, with a properly selected objective function, to eliminate resonance frequencies from the mechanical wave spectrum, which makes it possible to protect fragile monuments, exposed to destruction even at low force values.

References

[1] C. Marquis-favre, E. Premat, D. Aubrée, M. Vallet. *Noise and its Effects - A Review on Qualitative Aspects of Sound. Part I: Notions and Acoustic Ratings,* **Acta Acustica United with Acustica**, **91**, 2005, pp. 613–625.

[2] A.T. Lloret, S. Sendra, J. Lloret, R. Del Rey, M. Louis Cereceda, *Vibroacoustic Impact on the Architectonic Heritage When Using Replicas of 16th Century Weapons,* **Sensors**, **17**, 2017, 1871.

[3] S.H. Park, P.J. Lee, K.S. Yang, K.W. Kim, *Relationships between non-acoustic factors and subjective reactions to floor impact noise in apartment buildings* **The Journal of the Acoustical Society of America**, **139**, 2016, pp. 1158–1167.

[4] C. Scrosatia, F. Scamonia, A. Pratob, S. Secchic, P. Faustid, A. Astolfi, L. Barbaresi, F. D'Alessandro, A. Di Bella, G. Zambon, *Uncertainty of facade sound insulation by a Round Robin Test. Evaluations of low-frequency procedure and single numbers.* **Building and Environment**, **105**, 2016, pp. 253–266.

[5] S. Secchi, G. Cellai, P. Fausti, A. Santoni, N. Z. Martello, *Sound Transmission between Rooms with Curtain Wall Façades: A Case Study.* **Building Acoustics**, **22**, 2015, pp. 193–207.

[6] G.R. Watts, *Acoustic performance of parallel traffic noise barriers*, **Applied Acoustics**, **47**(2), 1996, pp. 95–119.

[7] M.S. Kushwaha, *Classical band structure of periodic elastic composites,* **International Journal of Modern Physics B**, **10**, 1996, pp. 977-1094.

[8] Y. Tanaka**,** T. Yano, S-I. Tamura, *Surface guided waves in two-dimensional phononic crystals*, **Wave Motion**, **44**, 2007, pp. 501–512.

[9] M. Sigalas, E. N. Economou, *Elastic and acoustic wave band-structure,* **Journal of Sound Vibration**, **158**(2), 1992, pp. 377-382.

[10] I. Spiousas, P.E. Etchemendy, E.R. Calcagno, M.C. Eguia, *Shifts in the Judgement of Distance to a Sound Source in the Presence of a Sonic Crystal*, **Proceedings of Meetings on Acoustics**, **19**, 2013, p. 050162.

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

[12] N. Côté, J.O. Vasseur, Q. Souron, C. HLADKY-HENNION, *Transformation of sound by a phononic crystal,* **Inter-Noise 2014**, Melbourne Australia, 16-19 November, 2014.

[13] M.P. Norton, D.G. Karczub, **Fundamentals of Noise and Vibration Analysis for Engineers** (second edition), Cambridge University Press, New York, 2003.

[14] S. Garus, W. Sochacki, *High-performance quasi one-dimensional mirrors of mechanical waves built of periodic and aperiodic structures*, **Journal of Applied Mathematics and Computational Mechanics, 17**(4), 2018, p. 19-24.

[15] O. Dazel, J.P. Groby, B. Brouard, C. Potel, *A stable method to model the acoustic response of multilayered structures*, **Journal of Applied Physics**, **113**, 2013, 083506.

[16] S. Garus, W. Sochacki, One dimensional phononic FDTD algorithm and Transfer Matrix Method implementation for Severin aperiodic multilayer, **Journal of Applied Mathematics and Computational Mechanics**, **16**(4), 2017, pp. 17-27.

[17] P.G. Luan, Z. Ye, *Acoustic wave propagation in an one-dimensional layered system,* **Physical Review E**, **63**(6), 2001, id. 066611.

[18] M.M. Sigalas, C.M. Soukoulis, *Elastic-wave propagation through disordered and/or absorptive layered systems*, **Physcal Review B**, **51**, 1995, 2780.

[19] S. Garus, W. Sochacki, M. Bold, *Comparison of Phononic Structures with Piezoelectric 0.62PB(MG1/3NB1/3)O3-0.38PBTIO3 Defect Layers*, **Engineering Mechanics 2018**, 2018, pp. 229-232.

[20] L. Han, Y. Zhang, Z.-Q. Ni, Z.-M. Zhang, L.-H. Jiang, *A modified transfer matrix method for the study of the bending vibration band structure in phononic crystal Euler beams,* **Physica B: Condensed Matter**, **407**, 2012, pp. 4579-4583.

[21] S. Garus, M. Bold, W. Sochacki, *Transmission in the Phononic Octagonal Lattice Made of an Amorphous Zr55Cu30Ni5Al10 Alloy,* **Acta Physica Polonica A, 135**(2), 2019, p. 139-142.

Received: February 26, 2019
Accepted: November 24, 2019