

# Optimization of double-layer sound absorber in a broadband frequency range using transfer matrix method and Evolution Strategies algorithm

Parviz Ghadimi<sup>\*</sup>, Morteza Gholamipour, and Mohammad A. Feizi Chekab

Department of Marine Technology, Amirkabir University of Technology, Tehran, Iran

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**Abstract.** Curtailment of the ambient noise level for providing a better living environment is immensely important. Accordingly, acoustic isolation via different combinations of porous materials is the most widely used passive soundproofing system. The present study focuses on the optimization of single and double-layer absorbers in different frequencies. To this end, the transfer matrix and the Evolution Strategy (ES) method are firstly explained. Afterward, the optimization of single and double-layer absorbers is considered for up to 10 parameters (material porosity, air gap, perforated plate characteristics among others) at 350 Hz frequency and has been compared with the results obtained through other methods (Genetic Algorithm among others). It has been illustrated that ES algorithm provides better optimization in this field. Subsequently, since the incident sound in most cases is a correlation of different frequencies, the broadband optimization of the single and double-layer absorbers is considered in three frequency ranges (100–800 Hz, 800–1600 Hz, 1600–3000 Hz), with an increment of 1 Hz, for three different materials (polyester, fiber and foam). After the optimization, the resulting optimum parameters are presented in form of characteristics charts of the optimized materials for different frequency ranges, as a reference for material designers and manufacturers. Also, the absorption coefficient of all optimized cases are calculated and presented in range of 100 Hz to 3 kHz as a reference for the absorber selection for different situations. Finally, by presenting the improvement chart of double layer versus single layer combinations, it has been shown that double layer combination can improve the absorption coefficient of different materials up to 4% in different frequencies depending on the material (4% for polyester and foam for under 800 Hz, 3–4% for polyester and fiber for 800–1600 Hz and 2.6% for foam in 1600–3000 Hz).

**Keywords:** Double-layer sound absorber / optimization / foam / fiber / polyester / transfer matrix / Evolution Strategy (ES) Algorithm / broadband frequency range

## 1 Introduction

In 1970, the World Health Organization (WHO) carried out an assessment about the global disease burden from the occupational noise in which the noise characteristics and their relevance to workers' health were studied and quantified. It was proved that high level of environmental noise in a working area is the main cause of worker's psychological and physiological diseases [1]. It has always been a challenge for engineers to design an optimized sound absorber in order to obtain suitable absorption in a broadband frequency range [2]. To achieve this goal, a combination of multi-layered absorbers has been proved to be very effective [2,3]. While porous materials have many applications in sound absorption, they only exhibit suitable

absorptive properties at high noise frequencies. Therefore, for an appropriate noise reduction and sound absorption in low frequency range, a resonator absorber is used as a coating for the porous material. This type of covering improves the absorption properties at low frequency noises while protecting the porous material. The absorption mechanism for this type of coating is based on the Helmholtz resonator function. The resonators can be of various types such as membrane, perforated plate, micro-perforated plate and slot plate while a perforated plate resonator is used in the present study as the coating for the porous material.

As far as porous sound absorbers are concerned, different models have been introduced which offer sound absorption coefficients using three different methods [4]; Empirical Model (EM), Phenomenological Model (PM) which is based on the cylindrical tube, and Microstructure Model (MM). The latter is based on a set of cylinders while air passes through them. Formulations of Delany and

<sup>\*</sup> e-mail: [pghadimi@aut.ac.ir](mailto:pghadimi@aut.ac.ir)

Bazley [5] are among many examples of the application of empirical models [6]. In the past couple of decades, great efforts have been exerted to use phenomenological models [7–16], while major contributions have been made to the application of microstructure models [17–21].

In order to achieve an optimum design, different optimization tools have been developed over the years. In the case of optimal noise control, sound absorption and transfer loss have been studied using Genetic Algorithm (GA), Simulated Annealing (SA), and Topology methods. As an example, Yoon [22] optimized fiber materials using topology method, while Duhring et al. [23] developed an acoustical design using this method of optimization. Different arrangements of porous layers have been studied by Lee et al. [24] in order to achieve maximum transfer loss based on topology method. In another attempt, Lee et al. [25] optimized two-dimensional foams for maximum sound absorption. In a similar approach, the efficiency of a muffler was improved using topology method [26], while Yoon et al. [27] optimized the acoustic-structure interaction problems using topology method. Simulated annealing method was also used by Ruiz et al. [3] in order to optimize the absorption properties of micro-perforated multi-layered panel. Also, the Genetic Algorithm (GA) optimization tool was used to improve the absorption characteristics of meta-materials by Meng et al. [28].

In the present study, first the single-layer absorber with a particular arrangement is optimized using Evolution Strategy (ES) algorithm and the obtained results are compared against those by Genetic Algorithm (GA) and Gradient methods at a particular noise frequency [29,30]. Subsequently, a double-layer sound absorber is optimized under thickness limitations at a particular frequency using ES and GA methods [31,32]. Accordingly, different characteristics of single-layer and double-layer sound absorbers are optimized to obtain the best absorption coefficients. This is done at three different frequency bands for three different porous materials of foam, fiber and polyester, using transfer matrix and ES optimization method. Later, by comparing the absorption coefficients of single and double-layer absorbers, the effectiveness of double-layer layout is evaluated for these materials.

In the next sections, the mathematical formulation of transfer matrix method and the Evolution Strategy is presented, followed by the optimization of single and double layer combinations of foam, fiber and polyester.

## 2 Mathematical formulation

Transfer matrix is a powerful method which is capable of modeling sound propagation in porous materials with or without resonator coatings. By this method, the assumption of plane wave is applied to the incident and transmitted waves through the absorber layers.

Impedance of any arbitrary surface is given by the relation [2]

$$z_{si+1} = \frac{-jz_{si}z_i \frac{k_{xi}}{k_i} \cot(k_{xi}d_i) + \left(z_i \frac{k_i}{k_{xi}}\right)^2}{z_{si} - jz_i \frac{k_i}{k_{xi}} \cot(k_{xi}d_i)}, \quad (1)$$

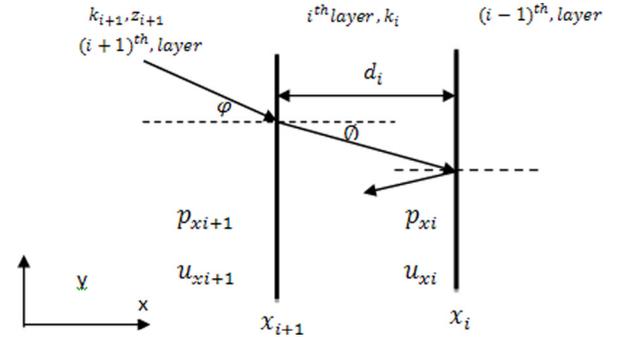


Fig. 1. Transfer matrix methodology for multi-layered absorbers.

in which  $z_{si+1}$  and  $z_{si}$  are impedances at  $X_{i+1}$  and  $X_i$ , respectively (as shown in Fig. 1), while  $k_i$  is wave number at the  $i$ th layer. When a hard backing is placed behind the absorber, the above formula is then reduced to equation (2) [2].

$$z_{si+1} = -jz_i \frac{k_i}{k_{xi}} \cot(k_{xi}d_i). \quad (2)$$

It is now possible to change equation (2) to conform to a single-layer absorber shown in Figure 2, as in

$$z_1 = -jz_0 + \cot(k_0L_0), \quad (3)$$

where

$$z_0 = \rho_0 c_0, k_0 = \frac{\omega}{c_0}. \quad (4)$$

Here,  $z_0$  and  $k_0$  are air impedance and wave number, respectively [2]. In the meantime, impedance for medium 2 can be written as [2]

$$z_2 = \frac{-jz_1 \times z_c \times \cot(kc \times L_1) + z_c^2}{z_1 - jz_c \times \cot(kc \times L_1)}. \quad (5)$$

Now, with the addition of  $z_2$  to  $z_p$ , the impedance of the absorber's surface can be evaluated as [2]

$$z_3 = z_2 + z_p. \quad (6)$$

Using empirical formulas [5], it is possible to calculate the impedance and wave number for the porous material by

$$k_c = \frac{\omega}{c_0} \left[ 1 + c_1 \left( \frac{\rho_0 f}{R} \right)^{c_2} + c_3 \left( \frac{\rho_0 f}{R} \right)^{c_4} \right]. \quad (7)$$

$$z_c = \rho_0 c_0 \left[ 1 + c_5 \left( \frac{\rho_0 f}{R} \right)^{c_6} + c_7 \left( \frac{\rho_0 f}{R} \right)^{c_8} \right]. \quad (8)$$

Coefficients  $c_i$  should be defined for each of the materials.

Additionally, equation (9) is used to evaluate the impedance on the surface of the perforated panel [33].

$$z_p = \frac{\rho_0}{\varepsilon} \sqrt{8\vartheta} \left( 1 + \frac{q}{2d} \right) + j \frac{\omega \rho_0}{\varepsilon} \left[ \sqrt{\frac{8\vartheta}{w}} \left( 1 + \frac{q}{2d} \right) + q + \delta \right]. \quad (9)$$

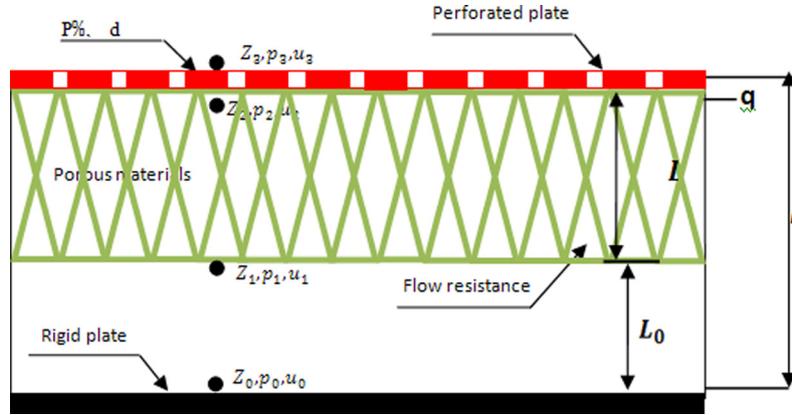


Fig. 2. Arrangement for a single-layer absorber.

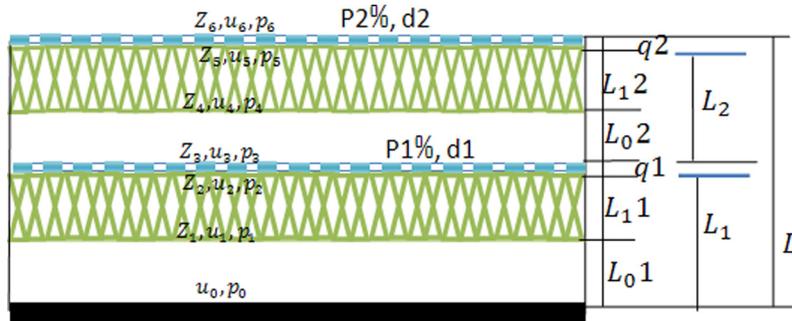


Fig. 3. Arrangement for a double-layer absorber.

$$\delta = 0.85(2d)(1 - 1.47\sqrt{\varepsilon} + 0.47\sqrt{\varepsilon^3}).$$

Consequently, equations of the absorption coefficient using transfer matrix approach for the single and double-layer sound absorbers can be formulated.

### 2.1 Absorption coefficient for single-layer absorbers

Absorption coefficient for a single-layer absorber (as shown in Fig. 2) is defined as follows:

$$\alpha = 1 - \left| \frac{z_3 - \rho_0 c_0}{z_3 + \rho_0 c_0} \right|^2 = \alpha(f, p\%, d, R, q, L_1, L_0), \quad (10)$$

where  $p\%$  and  $L$  are

$$p\% = \varepsilon * 100. \quad (11)$$

$$L = L_0 + L_1 + q. \quad (12)$$

### 2.2 Absorption coefficient for double-layer absorber

For a double or multi-layer sound absorber (shown in Fig. 3), the optimization parameters are defined as follows:

$$\alpha = 1 - \left| \frac{z_6 - \rho_0 c_0}{z_6 + \rho_0 c_0} \right|^2 = \alpha(f, p1\%, p2\%, d1, d2, R1, R2, q1, q2, L11, L01, L12, L02, rt1, rt2). \quad (13)$$

$$rt1 = \frac{L11}{L1}, rt2 = \frac{L22}{L2}, L2 = L - q1 - q2 - L1. \quad (14)$$

$$L01 = (1 - rt1) \times L1.$$

$$L02 = (1 - rt2) \times L2.$$

It should be noted that an absorption coefficient of unity stands for maximum possible sound absorption or total absorption of sound.

## 3 Evolution Strategy (ES) algorithm

The algorithm of Evolution Strategy (ES) was firstly introduced by Rothenberg [34] in 1973 as an innovative method. Steps that are performed in most of the ES algorithms:

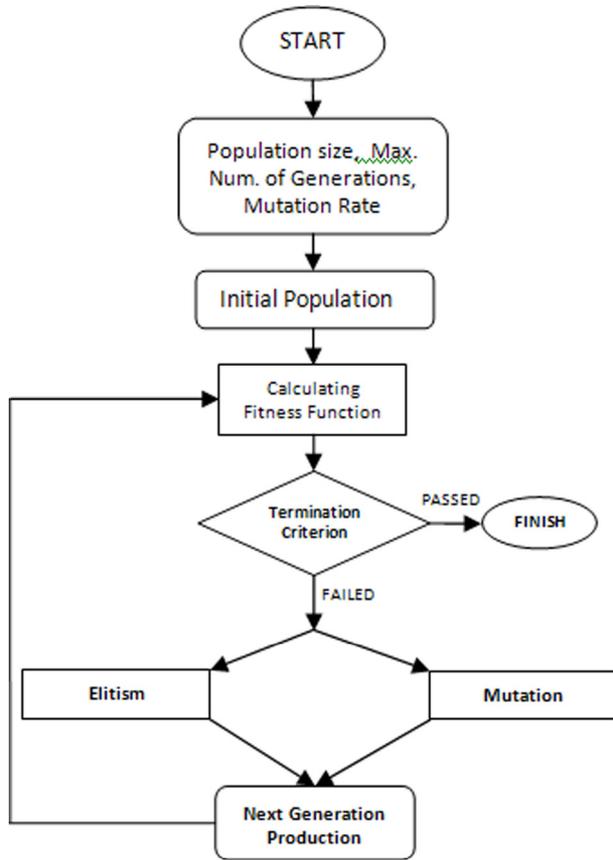
**Step 1:** Determination of population size, maximum number of generations, and mutation rate.

**Step 2:** Generation of the initial population (as parents) using random numbers (which gives a set of chromosomes).

**Step 3:** Calculation of fitness function for each chromosome.

**Step 4:** Evaluation of termination criterion, moving to Step 5 in case the criterion is not satisfied.

**Step 5:** Production of next generation using following methods:



**Fig. 4.** Flowchart of the applied Evolution Strategy (ES) algorithm.

- using elitism (selection of a particular number of elite chromosomes from the community);
- applying mutation to a particular set of community members (mutants) and the generation of children for the next generation;

**Step 6:** Returning to Steps 3 and 4.

For applying the ES algorithm to any desired problem, the operators and design parameters for the considered problem should be established, first. Optimization of a single or double-layer absorber using the ES algorithm is done in the same way and hence the operators of the absorption problem are introduced and discussed in this section.

A chromosome in ES algorithm is given as a set of  $(x_1, x_2, \dots, x_n, \sigma)$  in which  $x_i$  are the problem variables which are given as real numbers and  $\sigma$  is the step length for the mutation. The value of  $\sigma$  is determined using the one fifth success rule during the execution of the algorithm. Rothenberg [31] mathematically proved that, when the number of successful mutations accounts for one fifth of the unsuccessful mutations, the speed of convergence to the optimum solution increases. Based on this rule, in the present study, five variables are introduced. Each chromosome of the population has five genes which stand for the following parameters; Gene 1 for the porous material thickness ( $L_1$ ), Gene 2 for the specific resistance of porous material ( $R$ ), Gene 3 for the diameter of the holes on

the perforated panel ( $d$ ), Gene 4 for the porosity of the perforated panel ( $\varepsilon$ ) and Gene 5 for the total thickness of the absorber ( $L$ ). Therefore continuous random numbers are used for production of the initial generation (parents). It must be noted that these random numbers should not violate the limitations of the problem at hand. After producing the initial generation, a fitness function should be assigned to each chromosome. Based on this fitness function, some elite chromosomes will be chosen as new parents in order to be used for the mutation process which leads to production of children for the next generation. In the present study, normal mutation method is applied to the parent chromosomes to produce mutants. In this method of mutation, a random and normalized number is added to all genes, as shown in equation (15).

$$x'_i = x_i + N(0, \sigma). \quad (15)$$

It is noteworthy that after this mutation process, generated chromosomes that are theoretically impossible to be created, ought to be fixed. This basically means that the generated genes should not violate the limitation of the problem. If this situation does occur, the respective chromosome should be repaired. In order to repair the chromosome, the value of the violated gene should be set as the allowable limit for that parameter.

The process of elitism is used to generate the next generation. In other words, a particular number of elite chromosomes are chosen which will be transferred to the next generation. The rest of the required chromosomes for the next generation will be selected randomly from the chromosomes of the previous generation and the newly generated chromosomes resulting from the mutation process. The Evolution Strategy algorithm is continued until the termination criterion is fulfilled. The flowchart of the applied ES algorithm is illustrated in Figure 4.

## 4 Validation tests

In order to validate the results of optimization using Evolution Strategy algorithm, the obtained results are compared against the results of other methods in similar condition. Accordingly, the optimization results for both the single and double-layer absorbers are compared with the results of Chang et al. [30,31].

### 4.1 Single-layer absorber

The following limitations are set as the design and optimization parameters for the case of single-layer sound absorber which is intended to be optimized at a noise frequency of 350 Hz.

$$L_1 \leq .19(m); d \leq .015(m);$$

$$1000 \leq R \leq 50000 \left( \frac{\text{rayls}}{m} \right); p\% = 50. \quad (16)$$

Thickness of the perforated panel is kept fixed at  $q=0.01(m)$ . Therefore, to assess the validity of the Evolution Strategy optimization algorithm, the obtained

**Table 1.** Comparison of the optimization results using ES algorithm and other methods used by reference [29].

	$L_1$	$R$	$d$	$P\%$	$q$	$\alpha$
Evolutionary Strategy	0.090264	5793.038	0.015	3.6164	0.01	0.999999
Exterior penalty function method [29]	0.036	17459	0.0019	4.6	0.01	0.999857
Interior penalty function method [29]	0.050	7000	0.015	15	0.01	0.870331
Feasible direction method [29]	0.038	7563	0.015	14.9	0.01	0.879046
GA [29]	0.1286	39673	0.015	24.7	0.01	0.999943

**Table 2.** Optimization results in the case of double-layer absorber using Evolution Strategy and genetic algorithms.

	$p_1\%$	$p_2\%$	$d_1$	$d_2$	$rt_1$	$rt_2$	$R_1$	$R_2$	$L_1$	$\alpha$
GA	49.7	8.5	0.0132	0.0031	0.8658	0.9658	1039	44092	0.1186	0.938
ES	24.0	50.0	0.015	0.001	0.4346	0.0813	29843	6597	0.09	0.9600

**Table 3.** Coefficients ( $c_i$ ) for fiber, foam and polyester.

	$c_1$	$c_2$	$c_3$	$c_4$	$c_5$	$c_6$	$c_7$	$c_8$
Foam [35]	0.114	-0.369	-0.0985	-0.758	0.168	-0.715	0.136	-0.491
Fiber [5]	0.0571	-0.754	-0.087	-0.732	0.189	-0.595	0.0978	-0.700
Polyester [36]	0.078	-0.623	-0.074	-0.660	0.159	-0.571	0.121	-0.530

results using ES are compared against the results of reference [29] for similar design parameters, but using Genetic Algorithm (GA) and Gradient methods. The results of comparison are displayed in Table 1.

It is shown that by applying ES algorithm, higher absorption coefficient can be achieved, while other design parameters and limitations are respected. Therefore, the results of ES optimization are proved to be favorable.

## 4.2 Double-layer absorber

The design parameters and limitations of optimization for the double-layer absorber based on the studies of Chang et al. [31] are given as follows:

$$5 \leq p\%1, p\%2 \leq 50, 0.003 \leq d1, d2 \leq 0.015(m),$$

$$0 \leq rt1, rt2 \leq 1. \quad (17)$$

$$1000 \leq R1, R2 \leq 50000 \left( \frac{rays}{m} \right),$$

$$0.01 \leq L1 \leq 0.1888(m). \quad (18)$$

It should be noted that in the present study, thickness of the perforated plate for both layers are fixed at  $q=0.0006(m)=0.6(mm)$ , and other design parameters, as introduced in section 2, are as follows:

$$rt1 = \frac{L_1 1}{L_1}, rt2 = \frac{L_2 2}{L_2}, L_2 = L - q1 - q2 - L_1. \quad (19)$$

$$L_{01} = (1 - rt1) \times L_1.$$

$$L_{02} = (1 - rt2) \times L_2.$$

The results of optimization using Genetic Algorithm (GA) [31] and Evolution Strategy (ES) at a particular frequency of 350 Hz are displayed in Table 2.

## 5 Broadband optimization ES algorithm

Evolution Strategy (ES) algorithm has been proved to be a robust and effective tool for sound absorption optimization at a predefined frequency for both single and double layer sound absorbers. The algorithm is now implemented for

**Table 4.** The optimized parameters and the corresponding average absorption coefficients.

Optimized for	Single layer					Double layer									
	$P$	$d$	$R$	$L$	$\alpha$	$P_1$	$P_2$	$d_1$	$d_2$	$rt_1$	$rt_2$	$R_2$	$R_1$	$L_1$	$\alpha$
<b>Foam</b>															
100 Hz–800 Hz	0.012	0.015	16538	0.085	0.788	35.0%	1.4%	0.01	0.015	0.035	0.831	13618	8315.7	0.045	0.8037
800 Hz–1600 Hz	0.43	0.014	7444	0.073	0.984	38.2%	18.9%	0.015	0.01	0.035	0.831	12947	40309	0.045	0.9988
1600 Hz–3000 Hz	0.221	0.015	7243	0.085	0.986	46.0%	23.0%	0.01	0.01	0.035	0.831	9205.8	28176	0.0234	0.9994
<b>Fiber</b>															
100 Hz–800 Hz	0.021	0.015	19752	0.038	0.809	42.0%	2.1%	0.01	0.015	0.035	0.831	7799.6	15494	0.045	0.8121
800 Hz–1600 Hz	0.176	0.006	8158	0.071	0.985	38.2%	18.9%	0.015	0.01	0.035	0.831	12947	40309	0.045	0.9988
1600 Hz–3000 Hz	0.199	0.015	10025	0.085	0.991	28.0%	32.0%	0.014	0.01	0.035	0.831	8709.1	43342	0.0189	0.9996
<b>Polyester</b>															
100 Hz–800 Hz	0.02	0.015	23138	0.085	0.831	28.5%	1.9%	0.01	0.01	0.035	0.831	13075	8381	0.045	0.8224
800 Hz–1600 Hz	0.28	0.015	16538	0.058	0.984	26.5%	12.0%	0.015	0.01	0.035	0.831	10193	37900	0.041	0.9983
1600 Hz–3000 Hz	0.182	0.015	17286	0.085	0.991	14.1%	27.7%	0.015	0.015	0.035	0.831	10241	12741	0.0234	0.9891

optimization of single and double-layer absorbers in a broadband frequency range extending from 100 Hz to 3 kHz for three different materials of foam, fiber, and polyester.

This range is divided into three bands; low frequency from 100 Hz to 800 Hz, medium frequency from 800 Hz to 1600 Hz, and relatively high frequency from 1600 Hz to 3000 Hz. In each frequency range, the initial design parameters for both single and double-layer absorbers are selected randomly in the framework of design limitations and criteria. Subsequently, by a step of 1 Hz and using the transfer matrix method presented in Section 2, the absorption coefficients at each frequency are evaluated and ultimately the mean absorption coefficient in the entire range is calculated. This averaged parameter is then used as the fitness function for the algorithms of elitism and mutation in order to generate the next set of offspring for the next generation. The ultimate goal is to achieve a set of optimized design parameters which will result in the highest possible averaged absorption coefficient in the desired frequency range.

### 5.1 Broad-band optimization of single and double-layer materials

As described in the previous section, design parameters are initially selected randomly to give an initial averaged absorption coefficient for the selected frequency range, based on the formulas of transfer matrix approach. This averaged absorption coefficient is then maximized using the ES algorithm.

Before proceeding to the analysis and optimization, the coefficients ( $c_i$ ) for each material should be identified as in Table 3.

By substituting the values of these three materials in the single and double-layer optimization code and by defining the frequency range of the optimization, the best material properties for three ranges of frequency are determined. Therefore, eighteen optimized materials are obtained.

The resulting optimized parameters (defined in Sect. 2) and the mean absorption coefficients for different materials in different ranges are listed in Table 4.

### 5.2 Characteristics charts

To obtain a more comprehensive comparison of the optimized materials, a new “at a glance” representation is introduced in this section in which all material characteristics could be presented in a single chart, called the Characteristic Chart.

To illustrate all characteristics in one chart, the first difficulty is the large difference in the range of values for different characteristics. As an example, the values of flow resistivity are in the ten thousands scale, while the porosity is always under unity. Therefore, the values of all characteristics should be normalized first, i.e., a value between zero to one should be assigned to each characteristic. Here, the values of each parameter have been normalized using its maximum value over all materials. For example, in single-layer absorbers, all values of flow resistivity and porosity are divided by 23138 and 0.43 respectively, which are the maximum values of flow resistivity and porosity in all single-layer absorbers. Same operation is performed on other characteristics.

Aerward, a radar chart is used to plot the values of each material in one chart. In these charts, there are as many as the characteristics of the materials, i.e., 5 axes for single layer materials and 10 for double-layer absorbers. The characteristics chart of single and double layer foam optimized for 100–800 Hz is illustrated in Figure 5.

It is observed in Figure 5 that all characteristics of a material are shown in one chart and a good notion of the material characteristics is perceived.

In Figures 6 and 7, the optimized characteristics charts of each single and double-layer absorber in different frequency ranges are plotted together.

It is quite evident in these characteristics charts that parameters of a material may vary dramatically to obtain the best performance in the three ranges of frequency, especially the porosity, the flow resistivity, and the thickness of the absorber.

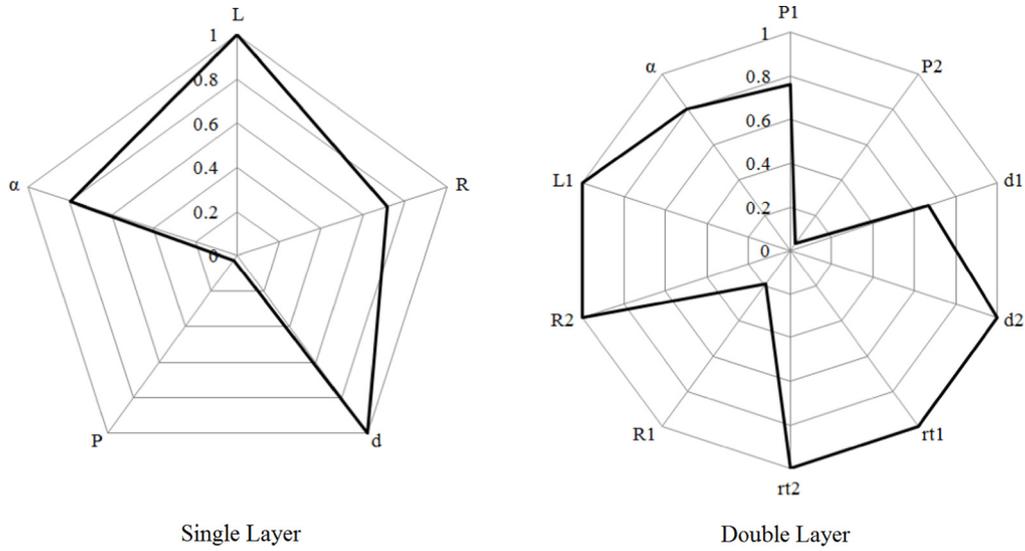


Fig. 5. Characteristics chart of single and double layer Foam optimized for 100–800 Hz.

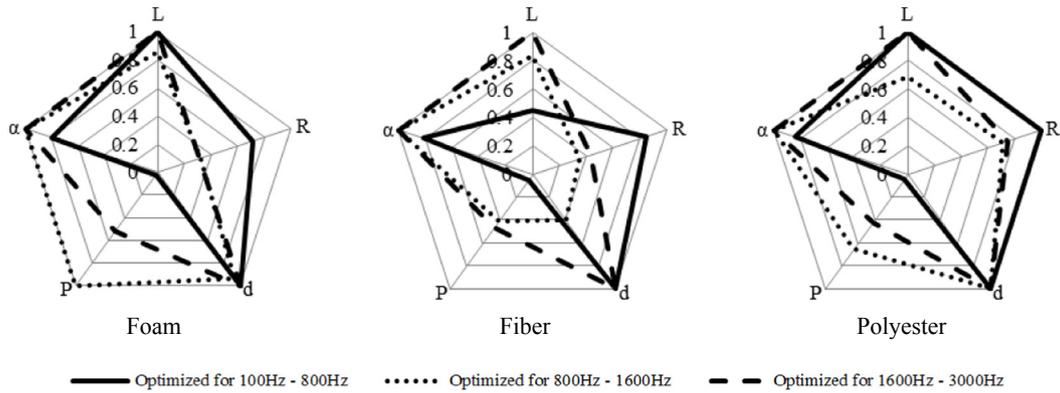


Fig. 6. Optimized characteristics chart of single-layer absorbers in three frequency ranges.

Although the average absorption coefficient is used as the target for optimization, it does not offer a good description of the performance of the absorber. Therefore, the absorption coefficient of the absorbers has been plotted vs. the frequency ranges in Figure 8.

As evidenced in Figure 8, for mid and high frequency ranges, double layer formation seems to improve the overall behavior of the absorber. However, for low frequencies, one may conclude that single layer formation is a better choice.

### 5.3 Efficacy analysis of double layer formation

For better assessment of the efficacy of the double layer formation in different frequencies and for different materials, the Improvement Percentage is defined as in equation (20).

$$\text{Improvement Perc.} \Big|_{\text{frequency}} = \frac{\alpha_{\text{Double layer}} - \alpha_{\text{Single layer}}}{\alpha_{\text{Single layer}}} \Big|_{\text{frequency}} \times 100. \quad (20)$$

The Improvement Percentage has been calculated for each formation and illustrated in Figure 9.

As observed in Figure 9, the maximum improvement obtained is slightly more than 4%. Also, it is observed that at low frequencies, foam is the only material improved by double layer formation. It is therefore deduced from Figure 9 that, although there is a slight improvement of the absorption coefficient, using double layer porous materials for the frequency ranges specified here requires careful design and optimization.

## 6 Conclusions

In the present study, Transfer Matrix approach and Evolution Strategy (ES) algorithm are used in order to achieve an optimized design for single and double-layer formations for Foam, Fiber and Polyester porous absorbers with maximum sound absorption.

Because of the fact that the main goal in many engineering and industrial applications is to obtain optimal absorption in a particular range of frequencies, the focus of the present study is to optimize the absorbers in order to have appropriate absorption properties in a broadband range of frequency. Single and double-layer absorbers are

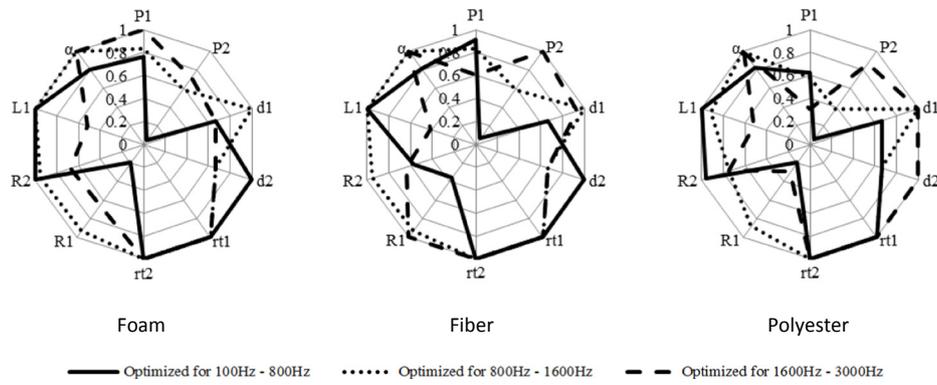


Fig. 7. Optimized characteristics chart of double-layer absorbers in three frequency ranges.

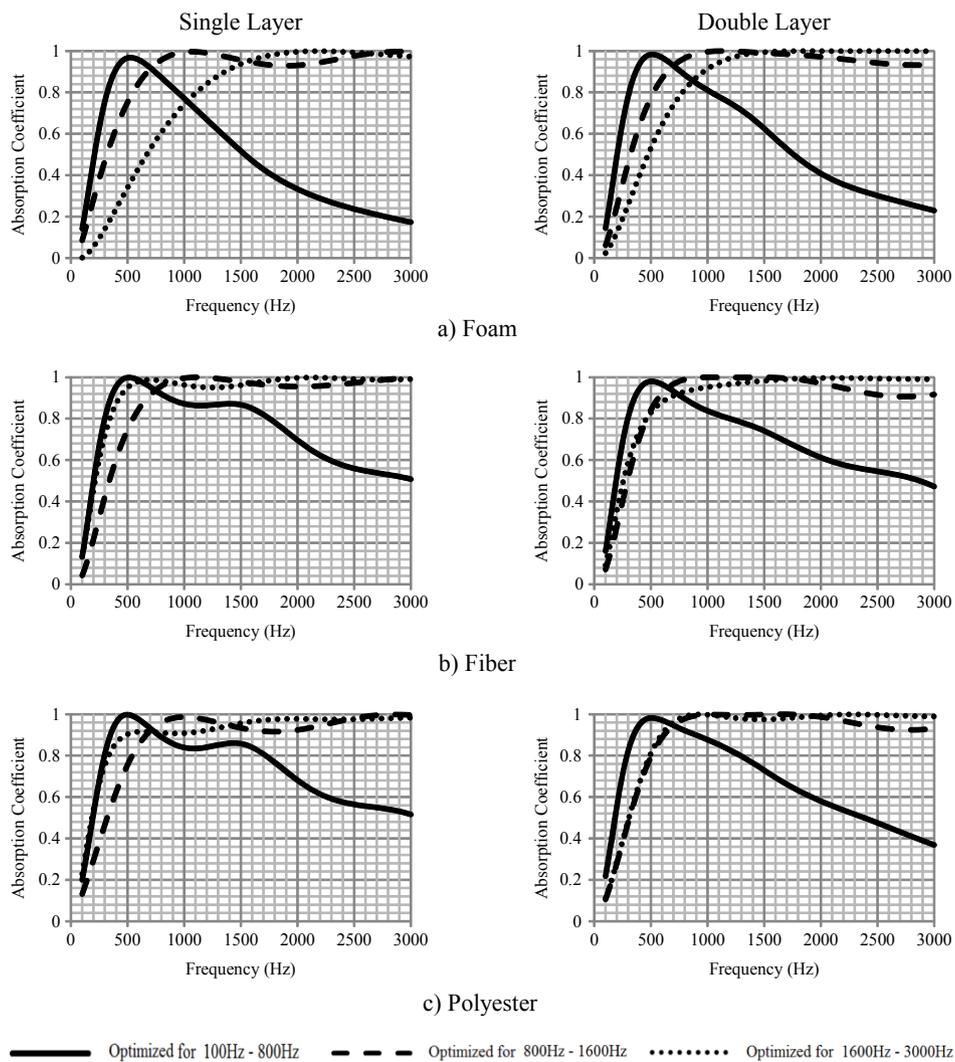


Fig. 8. Single and double-layer absorption coefficient versus frequency for different materials, optimized for three ranges of frequency.

first optimized at a particular frequency using the ES algorithm and the obtained results are compared with those using Genetic Algorithm (GA) and Gradient methods. This comparison proves that the ES algorithm

offers favorable results based on the limitations that are imposed on the design problem with superiority over the absorption coefficient obtained by the widely used method of Genetic Algorithm.

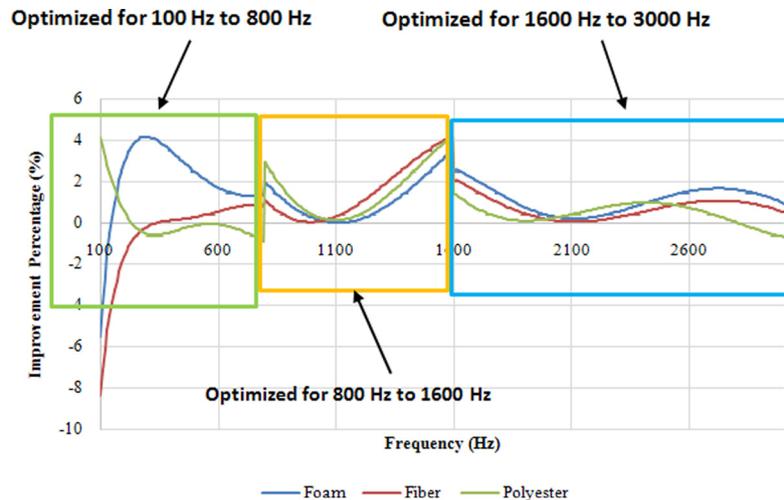


Fig. 9. Improvement percentage of the optimized materials for three ranges of frequency.

Single and double-layer absorbers are then optimized in three different frequency ranges extending from 100 Hz to 3000 Hz divided into three bands of low, medium and relatively high frequencies for three porous materials. The averaged absorption coefficients in each range of frequency are maximized using ES algorithm for both single and double-layer sound absorbers. To show the optimized parameters of absorbers, the characteristic charts of absorbers are introduced. Also, for a better assessment of the efficacy of the double layer formation, an Improvement percentage parameter has been defined and estimated for each optimized material and formation in each frequency range. The obtained results indicate that maximum improvement reached by the use of double-layer formation is slightly higher than 4%. Furthermore, it is shown that materials are differently affected by double layering. Accordingly, the improvement of absorption coefficient is 4% for polyester and foam below 800 Hz frequency, 3–4% for the polyester and fiber for 800 Hz–1600 Hz frequency and 2.6% for the foam for 1600 Hz–3000 Hz frequency. Overall, the presented findings indicate that, although there is a slight improvement of the absorption coefficient, using double layer porous materials for the frequency ranges specified here requires careful design and optimization.

The method of Evolution Strategy (ES) algorithm is also proved to be robust in the case of single and multi-layer sound absorber optimization problems.

## Compliance with ethical standards

Authors of this study received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The authors also declare that they have no conflict of interest.

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