Iranian Journal of Mechanical Engineering
The Iranian Society of Mechanical Engineers
Research Paper

DOI: 10.30506/jmee.2021.128422.1231

Investigation and Comparison of Three Popular Ultrasonic Generators (PZT, PVDF-EMFi) for Employing in Acoustic Scaling

S. Saffar*
Associate Professor

Acoustic scaling is one of the efficient techniques for measuring acoustic parameters of large and luxury places. Due to the range of acoustic scaling frequency, an airborne ultrasonic transducer has been used for transporting the power to the air. One major problem of ultrasonic transducers, radiating acoustic energy into the air, is to find the proper acoustic impedance of one or more matching layers. This work aims at developing an original solution to the acoustic impedance mismatch between transducer and air. Therefore we consider three piezoelectrics, PZT, PVDF, and EMFi transducers and air that have high acoustic impedance deference. We proposed the use of a genetic algorithm (GA) to select the best acoustic impedances for matching layers from the material database for a narrow band ultrasonic transducer that works at a frequency below the 1MHz by considering attenuation. This yields a highly more efficient transmission coefficient. Also, the results showed that by using the increasing number of layers we can increase our chance to find the best sets of materials with valuable both in acoustic impedance and low attenuation. Precisely, the transmission coefficient is almost higher than 80% for the more studied cases.

Keywords: Acoustic impedance, Matching layers, Ultrasonic transducers, Genetic Algorithm (GA), PZT, PVDF, EMFi

1 Introduction

A variety of acoustic methods are used to design and build important and sensitive halls and venues, concerts, or lectures where the quality of acoustic specifications is important and which is more cost-effective. One way is to create smaller-sized specimens with details such as chairs, curtains, and even small specimens inside the hall before the hall is built so that the acoustic conditions of the hall can be adjusted before the complex is fully constructed. This method is called acoustic scaling. The frequency of the acoustic modes is proportional to the dimensions of the hall, and the working frequency in the sculpted model must be increased in proportion to the amount of shrinkage of the hall dimensions to obtain accurate relations. With these interpretations, the frequency range in the scaled model is placed in the ultrasonic range. In this case, ordinary speakers will not be able to generate output with such a frequency range. Therefore, other tools must be used to produce high-frequency sound, and the design of airborne transducers can be a good option for this purpose. In this regard, the acoustic scaling

*Corresponding Author, Associate Professor, Department of Acoustics and Sound Engineering, IRIB University, P.O. Box 1986916511, Tehran, I.R. Iran, saffar@IRIBU.ac.ir
Receive: 2020/05/31 Accepted: 2021/09/07

method was first used on a 1: 5 scale using a dynamic source [1]. Afterward, other methods proposed solutions for acoustic scaling and compared the computer model with acoustic scaling [2, 3]. The rate of absorption of materials at high frequencies and adaptation to absorption at the main frequency in acoustic scaling mode were discussed in ref [4]. Therefore, ultrasonic transducers are the main pillar in acoustic scaling.

Ultrasonic transducers are needed in numerous machining, forming, medical, and non-destructive testing applications. However, there exists a problem of choosing an intermediate medium for impedance matching between the ultrasonic transducers and the medium to which ultrasonic energy had to be radiated. Depending on the kind of the loading medium, quarter-wave matching layers are usually proposed [5]. This can be obtained if materials of appropriate acoustic impedance are used. Although there are a lot of investigations who was concerned with piezoceramic transducers radiating a wave to liquids and biological structures (e.g. [5–8]), There are also a lot of papers were interested in the problem of matching the impedance of the ultrasonic transducer with a gas medium [9–15]. Some papers concentrate on design a narrow or broadband airborne ultrasonic transducer theoretically and experimentally by using one or two matching layers and some of them concentrate on fabricating the new materials with both low acoustic impedance and attenuation [16-22]. the matching layers for air load must have very low acoustic impedance. There is most material such as balsa or cork wood with low acoustic impedance. But unfortunately, these materials have a big attenuation in high frequency. In general, we can say that materials with low acoustic impedance have a high attenuation coefficient. Some researchers work on low acoustic impedance materials with low attenuation coefficient. For example, they present in their investigations that the polymeric membranes are more efficient than other porous materials such as silicon bubble in high frequency [23-27]. For showing the ability of the proposed method, we used almost the new material properties presented by Gomez in [28]. Theoretically, it is possible to apply one-, two- or multi-layer mechanical sets. Nevertheless, producing such layers requires high precision for transducers.

As the characteristic acoustic impedance of the Lead Zirconate Titanate pizo-electric (PZT) is $Z_p = 33\times 10^7\ \ \mathrm{kg}/\left(\mathrm{m}^2\cdot \mathrm{s}\right)$, which is highly greater than that of air ($Z_a = 427\ \mathrm{kg}/\left(\mathrm{m}^2\cdot \mathrm{s}\right)$), the two acoustic impedances must be matched in order to obtain an optimal energy transmission. This consists of adding one or several intermediate matching layers. Theoretically, solutions proposed in the literature consist of using one or more quarter-wave layers on the front face of the transducer. Practically, the possibilities, of finding a material with the required acoustic impedance, are rather limited. One research direction consists of elaborating new materials with desired acoustic impedance [5-8]. Alternatively, two or more layer schemes with readily available materials, of which the impedances decrease from 33 to 0.000427 Mrayl, can be used. Increasing the number of matching layers can offer a large range of available materials but can also induce more complexity in the fabrication process. However, this approach can enlarge the range of readily available materials that can be used for the matching layers.

The objective of this paper is the third fold. Firstly, we aim at comparing the analytical solutions to find the acoustic impedances of matching layers. Namely, we will compare the transmission coefficient obtained by using matching layers calculated with Chebyshev, Desilets, and Souquet theories [29-30]. Secondly, we interest in determining the loss in the transmission coefficient when the theoretical acoustic impedances are replaced by the nearest acoustic impedances of nowadays available materials.

Finally, we will apply a genetic algorithm (Dijkstra algorithm (DA) [31]) to determine the optimal acoustic impedances of matching layers. The acoustic impedances will be chosen from the available materials database. Therefore, the obtained acoustic impedances will correspond to readily available materials. This paper will be organized into five sections. Following this introduction, Section 2 deals with the theoretical framework of sound transmission through multilayer systems by considering the attenuation of layers. Subsequently, Section 3 is dedicated to the theoretical determination of matching layers by theoretical solutions proposed in the literature. An emphasis will be given on the loss in the transmission coefficients when replacing the theoretical acoustic impedances with the nearest acoustic impedances corresponding to most available materials (not theoretical acoustic values) and propose a different setup for a different number of layers for a narrow band ultrasonic transducer at frequency work less than 1 MHz. Before concluding, Section 4 will present the main contribution of this work; namely, the application of a genetic algorithm to calculate the acoustic impedance of the matching layers for a narrowband transducer that works in frequency less than 1 MHz.

2 Theory of wave propagation through multilayer

The situation for multilayer transmission is shown in Fig. 1. A plane attenuated longitudinal sound wave is propagating from left to right (the positive x direction) through a series of n layers of material of differing specific acoustic impedance. The incident wave travels through medium 1 and undergoes a series of reflections and transmissions in the subsequent layers until a transmitted wave emerges into medium n. The acoustic impedance and length of the kth layer ($1 \le k \le n$) are denoted z_k^* and l_k. The nth medium has an infinite length, i.e., $l_n = \infty$.

Subsequently, the following assumptions will be considered:

(i) The reflected wave in medium n is assumed to be nonexistent as this layer is assumed of infinite length,

(ii) Even though the bounded media would produce multiple reflections and transmissions in each layer, it is sufficient to suppose that there is only one wave in each propagating direction; provided that the boundary conditions are satisfied, these waves will include all the individual components

(iii) Actually, the PZT, which is used to generate the incident wave, consumes a part of the mechanical energy and converts it to an electrical one. However, this part of the mechanical energy will be neglected. This approximation is correct only if the transducer is open-circuit. The great mismatch in electrical impedance, between the transducer and the amplifier, would indicate that very little energy is lost in such a manner.

(iv) We consider the wave attenuate only due to the constant loss factor (η) and this value is in depended on frequency. This assumption is logical because we calculate the loss factor from the attenuation coefficient of materials in high frequency ($\approx$3 MHz). Therefore this is upper band estimation and if the set up work with this assumption then can work for fewer frequencies too.

Considering the first layer, we denote p_{i1} and v_{i1}, the incident wave pressure and particle velocity, respectively. Similarly, the reflected wave pressure and particle velocity are denoted p_{r1} and v_{r1}. Now let's focus on an intermediate medium, the kth medium (1<k<n). There are two waves propagating in opposite directions the transmitted and reflected waves. The transmitted wave has pressure p_{tk} and particle velocity v_{tk} and the reflected wave has p_{rk} and particle velocity v_{rk}. The nth layer has only one propagating wave as it is semi-infinite, the transmitted wave, of which the pressure and particle velocity are denoted p_{tn} and v_{tn}, respectively.

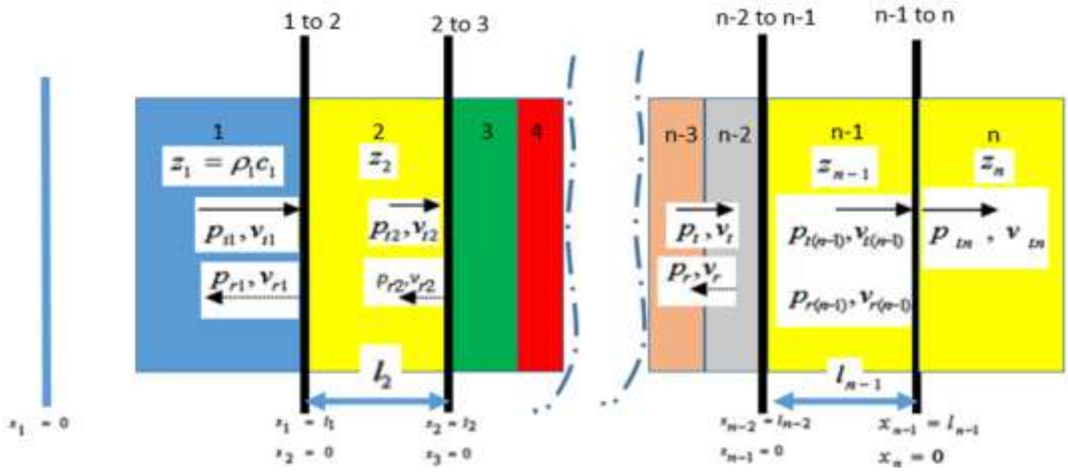

Figure 1 A plane longitudinal sound wave transmission

In order to link the pressures and the particle velocities in both the first and last medium, the mathematical induction method is used [32], which yields:

$$\begin{bmatrix} P_n(0) \\ V_n(0) \end{bmatrix} = \begin{bmatrix} P_{n-1}(l_{n-1}) \\ V_{n-1}(l_{n-1}) \end{bmatrix} = [T_{n-1}]\,[T_{n-2}]\cdots[T_3]\,[T_2] \begin{bmatrix} P_1(l_1) \\ V_1(l_1) \end{bmatrix}\ , \tag{1}$$

where

$$[T_k] = \frac{1}{2}\begin{bmatrix} \cos k_{1k} l_k g + j \sin k_{1k} l_k h & \dfrac{b \times z_k}{k_k}\left(\cos k_{1k} l_k h + j \sin k_{1k} l_k g\right) \\ \dfrac{k_k}{b \times z_k}\left(\cos k_{1k} l_k h + j \sin k_{1k} l_k g\right) & \cos k_{1k} l_k g + j \sin k_{1k} l_k h \end{bmatrix}, \quad (1 < k < n)$$

$$g = \left(e^{k_{2k} l_k} + e^{-k_{2k} l_k}\right);$$

$$h = \left(e^{-k_{2k} l_k} - e^{k_{2k} l_k}\right); \tag{2}$$

$$b = \left[k_{1k} - \eta_k k_{2k} + j\left(k_{2k} + \eta_k k_{1k}\right)\right]$$

is the transfer matrix of the k^th layer.

In this equation, z_k, l_k and η_k are the acoustic impedance, the thickness of the layer and the loss factor of the k^th layer, respectively. Also k_{1k} and k_{2k} are the real and imaginary part of complex wavenumber, k_k^*, for the k^th layer which can be calculated from the following:

$$E_k^* = E_k(1 + \eta_k j)$$

$$k_k^* = \frac{\omega}{c_k^*} = \frac{\omega}{\sqrt{\dfrac{E_k^*}{\rho_k}}} = \frac{\omega\sqrt{\rho_k}}{\sqrt{E_k(1+\eta_k j)}} = \omega\sqrt{\frac{\rho_k}{E_k'}}\,\frac{1}{\sqrt{(1+\eta_k j)}} = \frac{k}{\left(1+\eta_k^{\,2}\right)^{1/4}}\left(\cos\left(\frac{1}{2}\arctan\eta_k\right) - j\sin\left(\frac{1}{2}\arctan\eta_k\right)\right) = k_{1k} + jk_{2k} \tag{3}$$

$$k_{1k} = \frac{k_k}{\left(1+\eta_k^{\,2}\right)^{1/4}}\cos\left(\frac{1}{2}\arctan\eta_k\right)$$

$$k_{2k} = \frac{-k_k}{\left(1+\eta_k^{\,2}\right)^{1/4}}\sin\left(\frac{1}{2}\arctan\eta_k\right)$$

By considering in Eq. (1), the expressions of the pressure and the particle velocity given in ref [30], we obtain:

$$\begin{bmatrix} 1 & 1 \\ \dfrac{1}{z_n^*} & -\dfrac{1}{z_n^*} \end{bmatrix}\begin{bmatrix} A_n^* \\ B_n^* \end{bmatrix} = [T_{n-1}][T_{n-2}]\cdots[T_3][T_2]\begin{bmatrix} e^{-jk_1^* l_1} & e^{jk_1^* l_1} \\ \dfrac{1}{z_1^*}e^{-jk_1^* l_1} & -\dfrac{1}{z_1^*}e^{jk_1^* l_1} \end{bmatrix}\begin{bmatrix} A_1^* \\ B_1^* \end{bmatrix}, \tag{4}$$

or equivalently:

$$\begin{bmatrix} A_n^* \\ B_n^* \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{1}{z_n^*} & -\frac{1}{z_n^*} \end{bmatrix}^{-1} [T_{n-1}][T_{n-2}]\cdots[T_3][T_2] \begin{bmatrix} e^{-jk_1^* l_1} & e^{jk_1^* l_1} \\ \frac{1}{z_1^*} e^{-jk_1^* l_1} & -\frac{1}{z_1^*} e^{jk_1^* l_1} \end{bmatrix} \begin{bmatrix} A_1^* \\ B_1^* \end{bmatrix} . \tag{5}$$

where A_1^* and A_n^* are the complex amplitude of the incident pressure wave from the first and n^th layer, respectively. Also, B_1^* and B_n^* are the complex amplitude of the reflected pressure wave from the first and nth layer, respectively

As A_1^* is known and $B_n^* = 0$, Eq. (5) is a two linear equation system with two unknown variables. Hence, it can be solved to obtain A_n^* and B_1^*. Subsequently, we can deduce the sound-pressure transmission coefficient (PTC), for a system of n layers α_{pn}. This is given by

$$\alpha_{pn} = \left| \frac{A_n^*}{A_1^*} \right| . \tag{6}$$

According to the equation above, the physical meaning is that the transmission coefficient is a function of acoustic impedance of matching layers, their number, their internal loss and also matching layers thickness. Therefore, increasing the transmission coefficient is possible by choosing the right parameters and the right combination of them.

3 Calculation of matching layers impedances with a genetic algorithm

We recall that in this paper, we aim at calculating the acoustic impedance of the matching layers, i.e., $z_2, \ldots, z_{n-1}$ which give the maximum sound-pressure coefficients defined in Eq. (6). By considering a system of three layers, i.e., with only one matching medium, the Chebyshev, Desilets, and Souquet theories stipulate that the optimal transmission is obtained for [12]:

$$z_2^{(3),Ch} = \sqrt{z_1 \cdot z_3} \tag{7a}$$

$$z_2^{(3),Des} = \sqrt[3]{z_1 \cdot (z_3)^2} \tag{7b}$$

$$z_2^{(3),Sou} = \sqrt[3]{2 \cdot z_1 \cdot (z_3)^2} \tag{7c}$$

where $z_\nu^{(\mu),\chi}$ is the acoustic impedance of the ν^{th} layer of a system made of μ layers and obtained by the method χ. Eqs. (7) give the optimal acoustic impedance. However, this optimal value may not correspond to an existing material. To avoid conceiving a new material with the required acoustic impedance, we can use multiple matching layers. The above theories can be extended to this case. Precisely, in the general case of a system of μ layers $(\mu > 3)$, the optimal acoustic impedances are:

$$z_\nu^{(\mu),Ch} = \sqrt{z_{\nu-1}^{(\mu-1),Ch} \cdot z_{\nu+1}^{(\mu-1),Ch}} \ , \tag{8a}$$

$$z_\nu^{(\mu),Des} = \sqrt[3]{z_{\nu-1}^{(\mu-1),Des} \cdot \left(z_{\nu+1}^{(\mu-1),Des} \right)^2} \ , \tag{8b}$$

$$z_\nu^{(\mu),Sou} = \sqrt[3]{2 \cdot z_{\nu-1}^{(\mu-1),Sou} \cdot \left(z_{\nu+1}^{(\mu-1),Sou} \right)^2} \ . \tag{8c}$$

Furthermore, these theories assume that the matching layer lengths are of the form:

$$l_k = (2m-1)\frac{\lambda_k}{4} \tag{9}$$

where $\lambda_k = c_k / \omega$ is the wavelength and m is an integer number. That's why the optimal solutions are independent of the frequency. In the above theories, the acoustic impedance of the matching layers is independent of frequency. The frequency only affects the lengths of the layers which are calculated by using Eq. (9).
The results in the ref [32] written by the author, have shown the mentioned theories are not desirable for design multi-layer airborne ultrasonic transducers because of the following reason based on ref. [32]:

- The acoustic impedances obtained by Chebyshev, Desilets, and Souquet theories do not correspond always to nowadays available materials.
- Replacing these acoustic impedances by the nearest from a wide material database leads generally to a significantly lower transmission coefficient, mainly, when the number of layers is greater than or equal to four.
- Chebyshev theory gives more efficient matching layers than the two other theories.

The main problem of the above solutions is that the theoretical values are firstly chosen from a continuous set of possible values which is the set of strictly positive real numbers. Also ref. [32, 33] written by the author, propose a second solution. The optimal acoustic impedances are chosen from a discrete set corresponding to the material database. Moreover, the optimal values are obtained by a genetic algorithm.

3.1 Explanation of the written program

In this work, according to the Genetic algorithm (GA), a program was created by Matlab software. The detailed explanations about GA exist in ref [33]. The schematic is illustrated in Fig (4). In this program, a set of acoustic impedances as initial population due to several layers was generated randomly. These values must be between piezoelectric and air ($Z_a = 427\ \text{kg}/(\text{m}^2 \cdot \text{s})$).Hence, three different piezoelectrics (PZT, PVDF, and EMFi) as a source of vibration were employed and compared together. After that, the transmission coefficient was found with these acoustic impedances and the result was compared with the stop criteria (0.7). If this value is less than the stop value, these chromosomes change by the One Point Crossover method, and the calculation of transmission coefficient repeats, and the result checks with stop value, and so on. This procedure has done until the transmission coefficient be bigger than the stop value, in this state this set of chromosomes (acoustic impedances) accepted as a goal. This program can be run well for every number of layers.
For the summary, the genetic algorithm performs the following loop:

1. Randomly create an initial population (a set of acoustic impedances is generated as a chromosome),
2. Repeat,
3. Valuate the fitness of each individual,
4. Select one or more individuals from the population with a probability based on fitness to participate in genetic operations,
5. Create new individuals by applying genetic operations with specified probabilities,
6. Until an acceptable solution is found or some other stopping condition is met (transmission coefficient = 0.7),
7. Return the best-so-far individual.
8. Gene provides the implementation of the common genetic operator that called "One Point Crossover". In this step new chromosome chooses randomly one crossover point from parent chromosomes and creates a new offspring. One point crossover can look like table (1). (where "|" is the crossover point)

Table 1 Chromosomes and offspring relation

Chromosome 1	11101 | 001000
Chromosome 2	00001 | 010101
Offspring 1	11101 | 010101
Offspring 2	00001 | 001000

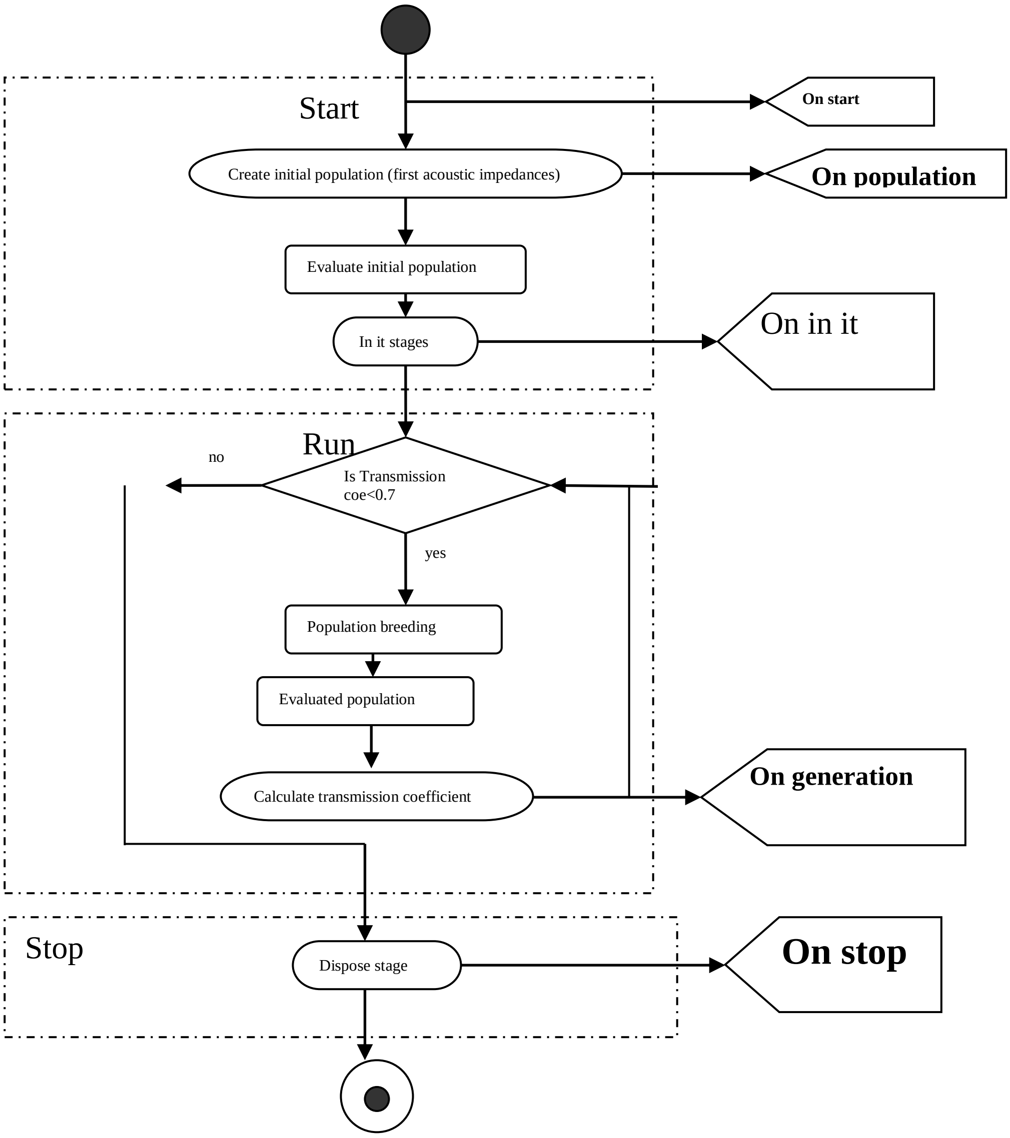

Figure 2 A schematic algorithm that is used in present work

In this case, we used the "simple mutator method" to modification. The simple mutator chooses randomly a mutation point and randomizes its gene. The mutation operator also needs a probability number that specifies its use. Generally, for a mutation operator, the probability is set to 20%. Jens provides a flexible structure for evolving a population of individuals.
Gene provides the implementation of the common genetic operator that called “One Point Crossover”. In this step new chromosome chooses randomly one crossover point from parent chromosomes and creates a new offspring. One point crossover can look like table (1). (where "|" is the crossover point) In this case, we used the "simple mutator method" to modification.

The simple mutator chooses randomly a mutation point and randomizes its gene. The mutation operator also needs a probability number that specifies its use. Generally, for a mutation operator, the probability is set to 20%. Jens provides a flexible structure for evolving a population of individuals.
They used a genetic algorithm is structured as depicted in Figure (2).
The algorithm execution passes through the following events:

- Start: the algorithm evolution starts. The random acoustic impedances are generated according to number of layers
- Init: internal structures, such as the population given as input at generation 0 and history, are initialized.
- Generation: a generation has been just performed.
- Stop: the algorithm terminates its executions. The stop criterion is amount of transmission coefficient and when it is more than 0.7 the process is terminated.

4 Results and discussion

To design a transducer it's enough to model the energy source such as PZT and matching layers by adding a backing layer in Abaqus software to find the longitudinal resonance frequency by changing backing and PZT and a bit near matching layer(s) thicknesses. For instance, figure (3) shows the PZT transducer for 4 layer works at resonance frequency after matching calculating and natural frequency analysis. Therefore, for the first step, we need to calculate the matching layers. In this work, we only focus on calculating the matching layer(s). To do that, we consider three ultrasound generators (PZT, PVDF, and EMFi) and air as media and concentrate to calculate the layers between them. By applying the above genetic algorithm (Section 3.1), we computed the acoustic impedances of matching layers for a total number of media (n) or (n-2) number of layers ranging from 3 to 8 in the frequency range of 0.02 to 1 MHz. The values of the optimal acoustic impedances are given in Tables (2) to (7). Furthermore, in our calculation, thicknesses are determined based on an odd number of $\frac{\lambda}{4}$. Indeed, 10 repetitions have been done for each ultrasound source (PZT, PVDF, EMFi) along with the transmission coefficient calculation but using the top 3.

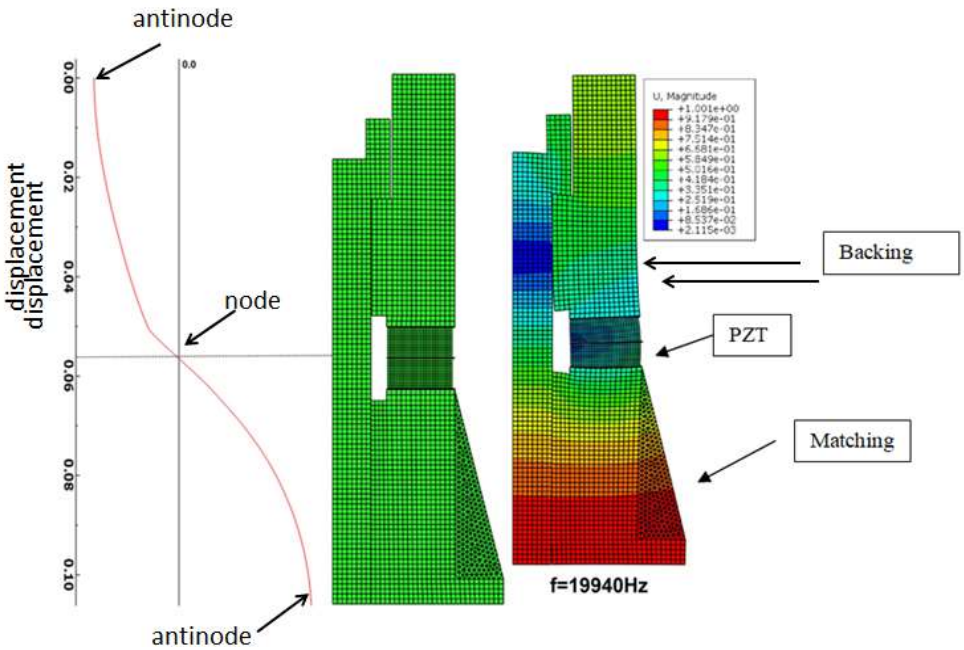

Figure 3 finding the longitudinal resonance mode of the transducer in Abaqus

Table 2 Sub-optimal solutions (n=3)

Z1(kg/m².s) Piezoelectric	Z2(kg/m².s) Matching layers	Z3(kg/m².s) Air	Transmission Co.
PZT 33000000	100000 polyethersulfone1	427	0.7
	131000 polyethersulfone2		0.731
	120000 Wood – cork		0.712
PVDF 3810000	84000 Cellulose nitrate1		0.72
	94000 mixed cellulose esters2		0.71
	35000 sillicone soft rubber bubble3		0.7
EMFi 26000	17000 PTFE		0.751
	11000 sillicone soft rubber bubble2		0.783
	8400 sillicone soft rubber bubble		0.761

Table 3 Sub-optimal solutions (n=4)

Z1(kg/m².s) Piezoelectric	Z2(kg/m².s) Matching layers	Z3(kg/m².s)	Z4(kg/m².s) Air	Transmission Co.
PZT 33000000	13100000 RTV-511	94000 mixed cellulose esters2	427	0.7868
	27300000 Titanium - mp=1725°C	109000 mixed cellulose esters3		0.7741
	20300000	35000 sillicone soft rubber bubble3		0.7316
PVDF 3810000	3110000 RTV-511	35000 sillicone soft rubber bubble3		0.7320
	2160000 Ecogel 1265, 100PHA OF B, outgass, 80C	35000 sillicone soft rubber bubble3		0.7590
	946245 SR	17000 PTFE		0.7146
EMFi 26000	11000 sillicone soft rubber bubble2	8400 sillicone soft rubber bubble		0.7825
	17000 PTFE	8400 sillicone soft rubber bubble		0.7718
	11000 sillicone soft rubber bubble2	8400 sillicone soft rubber bubble		0.7272

Table 4 Sub-optimal solutions (n=5)

Z1(kg/m².s)	Z2(kg/m².s)	Z3(kg/m².s)	Z4(kg/m².s)	Z5(kg/m².s)	Transmission Co.
Piezoelectric	**Matching layers**			**Air**	
PZT 33000000	19700000 Silicon - very anisotropic, values are approx.	16000000 Glass - flint	81000 polypropylene2	427	0.8326
	27300000 Titanium - mp=1725°C	19700000 Silicon - very anisotropic, values are approx.	162000 Nylon, 1		0.8285
	14090000 Glass - corning 0215 sheet	2100000 Neoprene	17000 PTFE		0.8410
PVDF 3810000	3680000 AMD Res-in-all - 502/118, 9:1	1840000 TPX-DX845, Dimethyl pentene polymer	35000 sillicone soft rubber bubble3		0.8491
	2330000 Polyethylene, high density, LB-861	360000 Expanded Expanded resin Glass resin Glass Filler balloons beads balloons 2	35000 sillicone soft rubber bubble3		0.8289
	2050000 Polyurethane, RP-6403	1680000 Polyurethane, RP-6422	35000 sillicone soft rubber bubble3		0.8833
EMFi 26000	17000 PTFE	11000 sillicone soft rubber bubble2	8400 sillicone soft rubber bubble		0.8399
	17000 PTFE	17000 PTFE	8400 sillicone soft rubber bubble		0.8714
	9550 sillicone soft rubber bubble1	8400 sillicone soft rubber bubble	8400 sillicone soft rubber bubble		0.8766

Table 5 Sub-optimal solutions (n=6)

Z1(kg/m².s)	Z2(kg/m².s)	Z3(kg/m².s)	Z4(kg/m².s)	Z5(kg/m².s)	Z6(k/m².s)	Transmission Co.
Piezoelectric	**Matching layers**				**Air**	
PZT 33000000	26400000 Boron carbide	17330000 Aluminum - rolled	1790000 Polyethylene, low density, NA-117	131000 RTV-511	427	0.8918
	23200000 Bearing babbit	7040000 Hysol - C9-4183/3561, 57.5phe C5W	4450000 DER317 - 9phr DEH20, 110phr W, r3	63000 sillicone soft rubber bubble4		0.8932
	20500000 Lead metaniobate	2000000 Butyl rubber	1570000 Wood - pine	60000 Silica aerogel		0.9040
PVDF 3810000	3210000 Epotek - V6, 10phA of B, r6	2770000 Polycarbonate, Black, Injection molded (Grade 141R, Color	1630000 Ecothane CPC-39	17000 PTFE		0.8933
	3270000 PVC, Grey, Rod Stock (normal	2500000 Tracon - 2143 D	2160000 Ecogel 1265, 100PHA OF B, outgass, 80C	35000 sillicone soft rubber bubble3		0.8854
	3300000 DER332 - 15phr mpda, 30phr LP3, 80°C cure	2160000 Ecogel 1265, 100PHA OF B, outgass, 80C	120000 Wood - cork	84000 Cellulose nitrate1		0.8627
EMFi 26000	17000 PTFE	11000 sillicone soft rubber bubble2	8400 sillicone soft rubber bubble	8400 sillicone soft rubber bubble		0.8859
	17000 PTFE	17000 PTFE	8400 sillicone soft rubber bubble	8400 sillicone soft rubber bubble		0.8961
	11000 sillicone soft rubber bubble2	11000 sillicone soft rubber bubble2	9550 sillicone soft rubber bubble1	8400 sillicone soft rubber bubble		0.9016

Table 6 Sub-optimal solutions (n=7)

Z1(kg/m²s)	**Z2(kg/m²s)**	**Z3(kg/m²s)**	**Z4(kg/m²s)**	**Z5(kg/m²s)**	**Z6(kg/m²s)**	**Z7(kg/m²s)**	**Transmission Co.**
Piezoelectric	Matching layers					Air	
PZT 33000000	26400000 Boron carbide	17630000 Duraluminin 17S	1350000 RTV-60/0.5% DBT @ 1.00MHz/10 PHR Toluene	1300000 Glass - silica	84000 Cellulose nitrate1	427	0.8278
	27300000 Titanium -	19700000 Silicon - very anisotropic, values are approx.	16000000 Glass - flint	988000 Boron nitride	150000 mixed cellulose esters7		0.8128
	24600000 Lead	11300000 DER332 - 15phr mpda, 6 micron W, r5	2520000 Polystyrene, Styron 666	1540000 Ecothane CPC-41	17000 PTFE		0.8058
PVDF 3810000	3700000 Scotchcast XR5235, 38 pha B, rt cure	1550000 Polyurethane, RP-6410	542070 MSR	256000 mixed cellulose esters8	17000 PTFE		0.8140
	1320000 RTV-21	1070000 RTV-118	946245 SR	542070 MSR	35000 sillicone soft rubber bubble3		0.8354
	3520000 Araldite - 502/956, 20phe C5W	2600000 Polyvinyl butyral, Butacite, (used to laminate safety glass together)	216000 Ecogel 1265, 100PHA OF B, outgass, 80C	542070 MSR	35000 sillicone soft rubber bubble3		0.8027
EMFi 26000	17000 PTFE	11000 sillicone soft rubber bubble2	11000 sillicone soft rubber bubble2	9550 sillicone soft rubber bubble1	8400 sillicone soft rubber bubble		0.8461
	17000 PTFE	11000 sillicone soft rubber bubble2	8400 sillicone soft rubber bubble	8400 sillicone soft rubber bubble	8400 sillicone soft rubber bubble		0.8342
	17000 PTFE	17000 PTFE	17000 PTFE	8400 sillicone soft rubber bubble	8400 sillicone soft rubber bubble		0.8202

Table 7 Sub-optimal solutions (n=8)

Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8(kg/m^2.s)	Transmission Co.
Piezoelectric (kg/m^2.s)	**Matching layers (1000kg/m^2.s)**						**Air(kg/m^2.s)**	
PZT 33000000	27300 Titanium - mp=1725° C	15300 Quartz - X-cut	8740 DER332 - 15phr mpda, SiC, r5	5580	160 microspheres ranging from 10 to 30 wt%	60 Silica aerogel	427	0.7278
	24000 Cadmium	17330 Aluminum - rolled	17330000 Aluminum - rolled	15300 Quartz - X-cut	990 RTV-112	123.480		0.7128
	30100 Zirconium, mp=1852° C, used in poison ivy lotion	27300 Titanium - mp=1725°C	26400000	10100 Glass - FK6 (large minimum order)	638	17 PTFE		0.7058
PVDF 3810000	2160 Ecogel 1265, 100PHA OF B, outgass, 80C	1660 Polyurethane, RP-6422	1600 Ethyl vinyl acetate, VE-634 (28% Acetate)	1120 Boron carbide	946.245 SR	17 PTFE		0.7140
	3700 Scotchcast XR5235, 38 pha B, rt cure	2760 Tapox epoxy	2630 Pellathane, Thermoplastic Urethane Rubber (55D durometer)	1570000 Wood - pine	360 Expanded Expanded resin Glass resin Glass Filler balloons	84 Cellulose nitrate1		0.7344
	3520 Araldite - 502/956, 20phe C5W	3270 PVC, Grey, Rod Stock (normal	3220 Epotek - V6, 10phA of B, 20phA LP3, r7	260000 Polyvinyl butyral, Butacite, (used to laminate safety glass)	990 RTV-112	17 PTFE		0.7067
EMFi 26000	17 PTFE	17 PTFE	11 sillicone soft rubber bubble2	8.400 sillicone soft rubber bubble	8.400 sillicone soft rubber bubble	8.400 sillicone soft rubber bubble		0.7481
	17 PTFE	17 PTFE	9.550 sillicone soft rubber bubble1	8.400 sillicone soft rubber bubble	8.400 sillicone soft rubber bubble	8.400 sillicone soft rubber bubble		0.7352
	17 PTFE	11 sillicone soft rubber bubble 2	9.550 sillicone soft rubber bubble1	8.400 sillicone soft rubber bubble	8.400 sillicone soft rubber bubble	8.400 sillicone soft rubber bubble		0.7302

As shown in Tables (2) to (7), the transmission coefficient from 3 layers increases and reach its maximum values for all ultrasonic generators (PZT, PVDF, and EMFi) in 6 layers. Afterward, the transmission coefficient decreases by increasing the number of layers. The reason is because of the higher loss in more layers. As shown in Tables (6) and (7), when there are seven and eight layers in the EMFi piezoelectric, layers of repetitive acoustic impedances are also produced, and the more layers, the greater the repetition due to the less difference in the acoustic impedance of the first medium (Piezoelectric) and the last (air). The optimal transmission coefficient obtained with the genetic algorithm corresponds to the 6th layers (Table 5). It is not mean that this set is the best one in all criteria such as manufacturing. It means that this is a good set for high transmission energy to the air load. But the existence of a lot of sets of layers by using GA is important because the flexibility can be increase. This is also the case of transmission coefficients corresponding to the exact values of acoustic impedances obtained by the Chebyshev theory. However, these theoretical acoustic impedances do not correspond systematically to available material. To achieve the theoretical transmission coefficients new materials should be designed which is far to be a simple task. Therefore, the genetic algorithm has a significant advantage to achieve very high transmission coefficients with available materials. Furthermore, the genetic algorithm yields sub-optimal solutions with a very good transmission coefficient and only by using the materials available in the database and not new ones. This is important if any material is expensive or there is a shortage in supply.

5 Conclusion

In this paper, we are interested in the calculation of the acoustic impedances of matching layers for airborne ultrasonic airborne transducers with three different piezoelectrics (PZT, PVDF, EMFi). A numerical method (using a genetic algorithm) is presented. The acoustic impedances are calculated for sake of optimal transmission coefficient.

The advantage of this method lies in the use of simple materials to make a matched transducer. According to the above results, we can make the following conclusions:

- The genetic algorithm solutions have the main advantage of corresponding to nowadays available materials. Moreover, they yield transmission coefficients almost equal to unity.
- For sake of flexibility, we can get, with a genetic algorithm, multiple sub-optimal solutions that have a very good transmission coefficient for each case (fixed number of layers).
- Also, the results showed, when the acoustic impedances between first (Piezoelectric) and last layers (Air) to below (for example between EMFi and air), the probability of repetition in layers increases in more layers (7 and more layers).
- The optimal transmission coefficient obtained with the genetic algorithm corresponds to the 6^{th} layer in the present study.

References

[1] Barron, M., “Developments in Concert Hall Acoustics in the 1960s” Theory and Practice, Vol. 1, pp. 538-548, (2019).

[2] Beranek, L., Jaffe, Ch., Nakajima, T., Kahle, E., Kirkegaard, R. L., and Clements, P., “How Acousticians Listen”, International Symposium on Room Acoustics, August 29-31, Melbourne, Australia, pp.1-8, (2010).

[3] Rindel, J.H., “Room Acoustic Modelling Techniques: a Comparison of a Scale Model and a Computer Model for a New Opera Theatre”. Building Acoustics, Vol. 18(3-4), pp. 259-280, (2011)

[4] Davoudi, B., and Morris, S. C., “Self-noise Modelling and Acoustic Scaling of an Axial Fan Configured with Rotating Controlled Diffusion Blade”, International Journal of Aeroacoustics, arXiv preprint arXiv:1812.10003, (2018).

[5] Desilets, C.S., Fraser, J.D., and Kino, G.S., “The Design of Efficient Broadband Piezoelectric Transducers”, IEEE Transactions on Sonics and Ultrasonics., Vol. 23(3), pp. 115-125, (1978).

[6] Goll, J.H., “the Design of Broad-Band Fluid-loaded Ultrasonic Transducers”, IEEE Transactions on Sonics and Ultrasonics., Vol. 26(6), pp. 385-393, (1979).

[7] Goll, J.H., and Auld, B.A., “Multilayer Impedance Matching Schemes for Broad Banding of Water Loaded Piezoelectric Transducers and High Q Electric Resonators”, IEEE Transactions on Sonics and Ultrasonics., Vol. 22(1), pp. 52-53, (1975).

[8] Souquet, J., Defranould, P., and Desbois, J., “Design of Low-loss Wide-band Ultrasonic Transducers for Non-invasive Medical Application”, IEEE Transactions on Sonics and Ultrasonics., Vol. 26(2), pp. 75-81, (1975).

[9] Highmore, P.J., “Impedance Matching at Ultrasonic Frequencies using Thin Transition Layers”, Ultrasonics International Conference Proceedings, June 8-11, London, England, pp. 12-116, (1973).

[10] Lynnworth, L.C., “Ultrasonic Impedance Matching from Solids to Gases”, IEEE Transactions on Sonics and Ultrasonics., Vol. 12(2), pp. 37-48, (1965).

[11] Tone, M., Yano, T., and Fukumoto, A., “High Frequency Ultrasonic Transducer Operating in Air”, Journal of Applied Physics. Vol. 23, pp. 436-438, (1984).

[12] Gudra, T., and Opielinski, K.J.,”Influence of Acoustic Impedance of Multi Layer Acoustic Systems on the Transfer Function of Ultrasonic Airborne Transducers”, Ultrasonics, Vol. 40, pp. 457-463, (2002).

[13] Opielinski, K.J., and Gudra, T., “Influence of the Thickness of Multi Layer Matching Systems on the Transfer Function of Ultrasonic Airborne Transducer”, Ultrasonics, Vol. 40, pp. 465-469, (2002).

[14] Gudra, T., and Opielinski, K.J., “Ultrasonic Transducers Working in the Air with the Continuous Wave within the 50–500 kHz Frequency Range”, Ultrasonics, Vol. 42, pp. 453-458, (2004).

[15] Kossof, G., “the Effects of Backing and Matching on the Performance of Piezoelectric Ceramic Transducers”, IEEE Transactions on Sonics and Ultrasonics, Vol. 13(1), pp. 20–30, (1966).

[16] Haller, M.I., and Khuri-Yakub, B.T., “Composites for Ultrasonic Air Transducers”, IEEE Ultrasonics symposium, Vol. 65(6), pp. 937–939, (1992).

[17] Toda, M., “Narrowband Impedance Matching Layer for High Efficiency Thickness Mode Ultrasonic Transducers”, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 49, pp. 210-218, (2002).

[18] Toda, M., “New Type of Matching Layer for Air-coupled Ultrasonic transducers”, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 49, pp. 345-351, (2002).

[19] Kelly, S.P, Hayward, G., and Alvarez-Arenas, T.E.G., “Characterisation and Assessment of an Integrated Matching Layer for Air Coupled Ultrasonic Applications”, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 51(10), pp. 1314-1323, (2004).

[20] Gomez, T. E., Arenas, A., F. R., Montero de Espinosa, M., and Rodríguez, A., “Viscoelasticity of Silica Aerogels at Ultrasonic Frequencies”, Journal of Applied Physics, Vol. 81, pp. 1198-1200, (2002).

[21] Gomez, T. E., Arenas, A., F. R., Montero de Espinosa, M., and Rodríguez, A., “Piezoelectric Transducers for Air-coupled Operation in the Frequency Range 0.3-2.5 MHZ”, Ultrasonics, Vol. 1, pp. 115-120, (2002).

[22] Ramadas, S.N., O’Leary, R.L., and Gachagan A., “Ultrasonic Sensor Design for NDE Application: Design Challenges & Considerations”, Centre for Ultrasonic Engineering, December 10-12, University of Strathclyde, Glasgow, UK, pp. 88-91, (2009).

[23] Gohari, H. D., Zarastvand, M.R., and Talebitooti, R., “Acoustic Performance Prediction of a Multi Layered Finite Cylinder Equipped with Porous Foam Media”, Journal of Vibration and Control, Vol. 26, pp. 899-912, (2020).

[24] Talebitooti, R., Zarastvand, M.R, and Darvishgohari, H., “Multi-objective Optimization Approach on Diffuse Sound Transmission through Poroelastic Composite Sandwich Structure”, Journal of Sandwich Structures & Materials, Vol. 23(4), pp. 1221-1252, (2021).

[25] Talebitooti, R., Zarastvand, M. R., and Gohari, H.D., “the Influence of Boundaries on Sound Insulation of the Multi Layered Aerospace Poro-elastic Composite Structure”, Aerospace Science and Technology, Vol. 80, pp. 452-471, (2018).

[26] Talebitooti, R., Gohari, H.D., and Zarastvand, M.R., “Multi Objective Optimization of Sound Transmission across Laminated Composite Cylindrical Shell Lined with Porous Core Investigating Non-dominated Sorting Genetic Algorithm”, Aerospace Science and Technology, Vol. 69, pp. 269-280, (2017).

[27] Talebitooti, R., and Zarastvand, M.R., “the Effect of Nature of Porous Material on Diffuse Field Acoustic Transmission of the Sandwich Aerospace Composite Doubly Curved Shell”, Aerospace Science and Technology, Vol. 78, pp. 157-170, (2018).

[28] Gomez, T. E., and Arenas, A., “Acoustic Impedance Matching of Piezoelectric Transducers to the Air”, IEEE Transaction on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 51, pp. 220-225, (2004).

[29] Thiagarajan, S., Martin, R.W., Proctor, A., Jayawadena, I., and Silverstein, F., “Dual Layer Matching (20 MHz) Piezoelectric Transducers with Glass and Parylene”, IEEE Transaction on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 44 (5), pp. 1172-1174, (1997).

[30] Kim, Y.B., and Roh, Y., "New Design of Matching Layers for High Power and Wide Band Ultrasonic Transducers", Sensors and Actuators a: Physical, Vol. 71(1-2), pp.116-122, (1998).

[31] B. Golden, "Technical Note-Shortest-Path Algorithms: a Comparison", Operations Research, Vol. 24 (6), pp.1164-1168, (1976).

[32] Saffar, S., and Abdullah, A., "Determination of Acoustic Impedances of Multi Matching Layers for Narrowband Ultrasonic Airborne Transducers at Frequencies <2.5 MHz – Application of a Genetic Algorithm", Ultrasonics, Vol. 52, pp. 169-185, (2012).

[33] Saffar, S., and Abdullah, A., "Influence of the Thickness of Matching Layers on Narrow band Transmitter Ultrasonic Airborne Transducers with Frequencies <100 kHz: Application of a Genetic Algorithm", Journal of Applied Acoustics, Vol. 75, pp.72-85, (2014).

Nomenclature

p_i	incident wave pressure
v_i	incident wave particle velocity
p_r	reflected wave pressure
v_r	reflected wave particle velocity
p_r	transmitted wave pressure
v_r	transmitted wave particle velocity
λ_k	wavelength
$f(Hz)$	resonance frequency
$\rho\left(\frac{kg}{m^3}\right)$	density
$\omega\left(\frac{1}{s}\right)$	angular frequency
$c\left(\frac{m}{s}\right)$	speed of sound
$z\left(\frac{N\cdot s}{m}\right)$	specific acoustical impedance
$Z\left(\frac{N\cdot s}{m^5}\right)$	acoustic Impedance
$z_0\left(\frac{N\cdot s}{m^3}\right)$	characteristic impedance
k_k^*	complex wavenumber
η_k	loss factor of the kth layer
A_1^*	complex amplitude of the incident pressure wave from the first layer
A_n^*	complex amplitude of the incident pressure wave from the nth layer
α_{pn}	sound-pressure transmission coefficient