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Research Paper

Optimal Selection of Multicomponent Matching Layers for Piezoelectric Transducers using Genetic Algorithm

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One major problem in the design of ultrasonic transducers results from a huge impedance mismatch between piezoelectric ceramics and the loading medium (e.g. gaseous, liquid, and biological media). Solving this problem requires the use of a matching layer (or layers). Optimal selection of materials functioning as matching layers for piezoelectric transducers used in transmitting and receiving ultrasound waves strictly depends on the type of the medium receiving the ultrasound energy. Several methods allow optimal selection of materials used as matching layers. When using a single matching layer, its impedance can be calculated on the basis of the Chebyshev, DeSilets or Souquet criteria. In the general case, the typically applied methods use an analogy to a transmission line in order to calculate the transmission coefficient T. This paper presents an extension of transmission coefficient calculations with additional regard to the attenuation coefficients of particular layers. The transmission coefficient T is optimised on the basis of a genetic algorithm method. The obtained results indicate a significant divergence between the classical calculation methods and the genetic algorithm method.

Keywords: acoustic impedance; matching layers; ultrasonic transducers.

1. Introduction

Broad application of ultrasound waves in numerous fields of technology requires ultrasound transducers to be adjusted to operating in various media: gases, liquids, and solids. In the case of piezoceramic transducers, one of the main problems to be solved results from huge acoustic impedance differences between the ceramic material and the operating environment of the transducer. This impedance mismatch has a significantly negative impact on the efficiency of ultrasound energy transmission from the transducer to the particular medium. One of the parameters for evaluating the operating efficiency of a transducer is the transmission coefficient T, which defines the relationship between the power dissipated at the load and the power at the source. Table 1 shows the value of this coefficient for several piezoceramic materials operated in air ($Z = 427$ Rayl) and water ($Z = 1.5 \cdot 10^6$ Rayl).

The data shown in Table 1 indicate that the problem of impedance mismatch is important for efficient energy transmission from the transducer (especially when the transducer is operated in air). The literature mentions a number of methods used to solve this

Table 1. Values of T for transmission from various piezoelectric materials into water and air (Nakamura *et al.*, 2012).

Material	Density ρ [kg/m^3]	Velocity c_L [m/s]	Acoustic impedance Z [MRayl]	T (water)	T (air)
Quartz SiO_2	2650	5760	15.3	0.325	$10.8 \cdot 10^{-5}$
PZT-5A	7750	3880	30.0	0.181	$5.5 \cdot 10^{-5}$
$PbNb_2O_6$	5800	2800	16.0	0.313	$10.3 \cdot 10^{-5}$
PVDV	1780	2260	4.6	0.742	$35.9 \cdot 10^{-5}$

problem (Nakamura *et al.*, 2012; Goll, 1979; Alvarez-Arenas, 2004; Qian, Harris, 2014; Ilham *et al.*, 2016). One of the most common methods is to use a matching layer or an arrangement of such layers (Pedersen *et al.*, 1982; Hamidimioglu, KhuriYakub, 1990; Łypacewicz, Duriasz, 1992; Gudra, Opielinski, 2002; Toda, Thompson, 2010; 2012; Fang *et al.*, 2016; Wang *et al.*, 2018). The optimal choice of materials functioning as matching layers for piezoelectric transducers used in the transmission and receiving of ultrasound waves strictly depends on the type of the medium into which ultrasound energy is transmitted and on the desired parameters of the pulse at the output of the transducer. These parameters may include ultrasound pulse shape, pulse energy, amplitude-phase characteristics of transducer admittance, transmission bandwidth, and band shape. The simplest method to match the transducer to the load is by using a quarter-wave layer. Multilayer systems may offer an improved match. However, in this case the choice of proper materials for the matching layer (or layers) becomes a new problem.

Values of acoustic impedances for matching layers, as offered by various authors in the literature, differ depending on the premises used by the authors in their calculations. The most commonly used formulas are those derived for long electric lines (the Chebyshev criterion, Goll, 1979), in which matching layer impedance is calculated as a geometric average of the ceramic impedance Z_c and the medium impedance Z_m:

$$Z_{\text{layer}} = (Z_c \cdot Z_m)^{1/2}. \tag{1}$$

The matching layer acoustic impedance calculated on the basis of the Chebyshev criterion provides the transmission coefficient value equal to 1 for layer thickness $\lambda/4$ (with no attenuation assumed).

The goal of the analysis performed by DeSilets *et al.* (1978) was to obtain an optimal pulse shape. In such a case, matching layer impedance is calculated on the basis of the following relationship:

$$Z_{\text{layer}} = (Z_c \cdot Z_m^2)^{1/3}. \tag{2}$$

Souquet *et al.* (1979) demonstrated that the maximum amplitude may be obtained if a condition of equal goodness between the electric branch and the mechanical branch in the transducer equivalent circuit is met when calculating matching layer impedance. In that case, the matching layer impedance is as follows:

$$Z_{\text{layer}} = (2Z_c \cdot Z_m^2)^{1/3}. \tag{3}$$

Criteria (1)–(3) may be generalised to include the case of a transducer with many matching layers, so as to allow calculations of acoustic impedance for individual layers.

With the use of the Chebyshev, DeSilets and Souquet criteria, matching layers are selected only on the basis of acoustic impedance values for individual materials. An analysis of a great number of scientific publications on the design of piezoceramic transducers indicates that their primary focus is on investigating the influence of matching layer impedance on transducer efficiency, and only secondary one is on other factors. One of such other factors is acoustic attenuation of the matching layer material. Attenuation (amplitude decrease) of an ultrasound wave along its propagation path in an actual medium is characterised by the use of an amplitude or an energy attenuation coefficient. Amplitude attenuation coefficient α describes a relative decrease of the amplitude per unit of wave travel distance. Analogically, energy attenuation coefficient is defined as a relative decrease of wave intensity per unit of wave travel distance. Wave attenuation is characteristic of a articular medium (material) and is determined by direct measurement. The value of attenuation is expressed in Np/m (or dB/m). Because attenuation depends on the frequency of a wave propagating in a particular medium, other units are also used, e.g. Np/(m $\cdot$ Hz) or dB/(m $\cdot$ Hz). The value γ, which describes attenuation along a single wavelength ($\gamma = \alpha \cdot \lambda$), is a very useful coefficient.

The influence of the attenuation properties of the matching layer material on the losses in the energy transmitted by the transducer was analysed by Alvarez-Arenas (2004). Figures 1 and 2 show the relationship between the transmission coefficient T and the acoustic impedance values, as well as the matching layer attenuation coefficient for the transducer operated in air and in water. Although the transmission coefficient was calculated from relationships obtained on the basis of a schematic for a different equivalent transducer than in (Alvarez-Arenas, 2004), the results are practically identical.

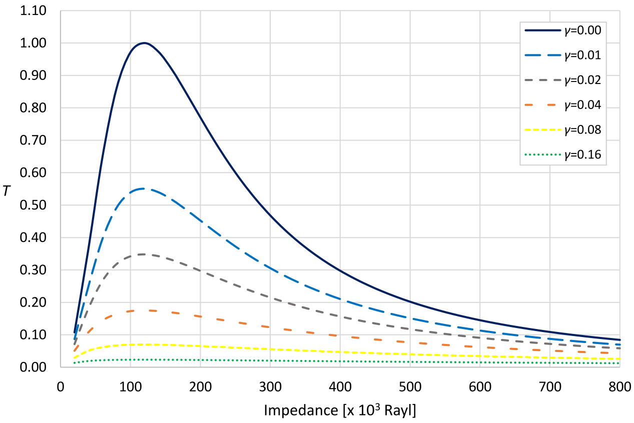

Fig. 1. Influence of the attenuation coefficient and acoustic impedance of the matching layer for air (attenuation coefficient per wavelength $\gamma = \alpha \cdot \lambda$ in Np).

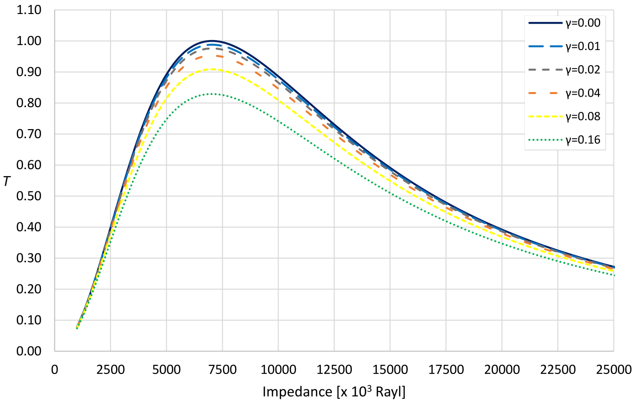

Fig. 2. Influence of the attenuation coefficient and acoustic impedance of the matching layer for water (attenuation coefficient per wavelength $\gamma = \alpha \cdot \lambda$ in Np).

The presented data indicate that the attenuation of the matching layer has a significant influence, especially in the case of air. When selecting a material for the matching layer, its attenuation may have a greater significance than the impedance value.

2. The model of the piezoelectric transducer with multicomponent matching layers

The basic parameter used in the evaluation of the match between the acoustic impedance of an ultrasound transducer and the acoustic impedance of the medium is the energy transmission coefficient T. It defines the ratio between the power dissipated at the load and the power at the source. In the case of a transducer with a single matching layer, the value of the coefficient T may be calculated from the following formula (Lynworth, 1965):

$$T = \frac{4Z_1}{|Z_1 + Z_{WE}|^2} \operatorname{Re}(Z_{WE}), \tag{4}$$

where

$$Z_{WE} = Z_2 \left[\frac{Z_T \cos(kd) + jZ_2 \sin(kd)}{Z_2 \cos(kd) + jZ_T \sin(kd)} \right]. \tag{5}$$

In the above equations, symbols Z_1, Z_2, and Z_T indicate respectively impedance of the ceramic in the transducer, impedance of the matching layer, and the impedance of the medium (coefficient k is the wave constant, and d is the thickness of the matching layer). The above equations may be generalised to take into account the case of a transducer with multi-matching layers. However, these equations do not account for the attenuation in the matching layer.

As it has been demonstrated in the previous section, taking into consideration the attenuation of each of the matching layers may be important in their selection. Transmission of elastic waves through a multilayer solid medium was first investigated in (Thomson, 1950). The publication offered a matrix-based solution to the analysed problem. In the analysis, the attenuated, longitudinal plane sound wave is assumed to propagate through a system of N layers of materials having different acoustic impedances. Figure 3 shows a physical model of a piezoelectric transducer with multiple matching layers.

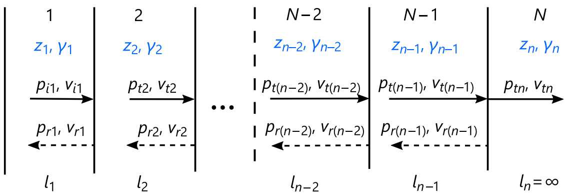

Fig. 3. Piezoceramic transducer with multiple matching layers.

In the case of the first layer, symbols p_{i1} and v_{i1} indicate respectively the pressure and the speed of particles in the incident wave. Analogically, the pressure and the speed of particles in the reflected wave are indicated with symbols p_{r1} and v_{r1}. In the intermediate layers, two waves propagating in reverse directions may be distinguished: the transmitted wave (symbols p_{tk}, v_{tk}) and the reflected wave (symbols p_{rk}, v_{rk}).

Acoustic impedances of the layers and their attenuations are indicated with respective symbols z_k^* and γ_k ($1 \le k \le N$). In the general case, the acoustic impedance of the k-th layer is a complex value. Symbols l_k indicate the thicknesses of individual layers. The first layer ($k = 1$) is the material of the ceramic in the transducer, while the last layer ($k = N$) is the medium into which ultrasound energy is transmitted from the transducer (thus an assumption that $l_N = \infty$). At the boundary between each of the layers, the incident wave is partially reflected and partially transmitted into the successive medium. In addition, when passing through successive layers, the wave is attenuated. Let symbols A_k^* and B_k^* indicate amplitudes of the transmitted wave and of the wave reflected in layer k, respectively. In the general case, these values should be considered as complex values. The propagation of an ultrasound wave through a system of N layers is then described by the following equation (Saffar, Abdullah, 2012; Saffar *et al.*, 2014):

$$\begin{bmatrix} A_N^* \\ B_N^* \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{1}{z_N^*} & -\frac{1}{z_N^*} \end{bmatrix}^{-1} [T_{N-1}] \dots [T_2][T_1] \begin{bmatrix} A_1^* \\ B_1^* \end{bmatrix}, \tag{6}$$

where

$$[T_1] = \begin{bmatrix} e^{-jk_1^* l_1} & e^{jk_1^* l_1} \\ \frac{1}{z_1^*} e^{-jk_1^* l_1} & -\frac{1}{z_1^*} e^{jk_1^* l_1} \end{bmatrix}, \tag{7}$$

$$[T_k] = \frac{1}{2} \begin{bmatrix} t_1 & -\frac{t_3}{k_k} t_2 \\ \frac{k_k}{t_3} t_2 & t_1 \end{bmatrix} \quad \text{for} \quad k = 2, \dots, N-1, \tag{8}$$

$$t_1 = \cos k_{1k} l_k \left(e^{k_{2k} l_k} + e^{-k_{2k} l_k}\right) + j \sin k_{1k} l_k (e^{-k_{2k} l_k} - e^{-k_{2k} l_k}),$$

$$t_2 = \cos k_{1k} l_k \left(e^{-k_{2k} l_k} - e^{k_{2k} l_k}\right) + j \sin k_{1k} l_k (e^{-k_{2k} l_k} + e^{k_{2k} l_k}),$$

$$t_3 = z_k \left[k_{1k} - \eta k_{2k} + j\left(k_{2k} - \eta k_{1k}\right)\right].$$

Symbols T_k in Eq. (6) indicate transmission matrices for the successive layers. If the value of A_1^* is known and if $B_N^* = 0$ (the last layer is limitless), relationship (6) provides a system of two linear equations with two unknowns. Solving these equations provides the values of A_N^* and B_1^*. This may serve as the basis to calculate energy transmission coefficient for a system of N layers T_{wN}:

$$T_{wN} = \left|\frac{z_1^*}{z_N^*}\right| \left|\frac{A_N^*}{A_1^*}\right|^2. \qquad (9)$$

In the above equations, the influence of attenuation in the matching layers is allowed for in the value of the wave constant, which is a complex value (Saffar, Abdullah, 2012):

$$k_i^* = k_{1i} + j k_{2i} = \frac{k_i}{\left(1+\eta^2\right)^{1/2}} \cdot \left[\cos\left(\frac{1}{2}\arctan(\eta)\right) - j \sin\left(\frac{1}{2}\arctan(\eta)\right)\right], \qquad (10)$$

where

$$\eta = \gamma / \pi.$$

Detailed calculations for the above relationships are provided in (Saffar, Abdullah, 2012).

3. Selection of matching layers using a genetic algorithm

Classical methods allow calculations of acoustic impedances for a matching layer (or layers) depending on the impedances of the transducer and of the medium. However, the calculated values frequently remain theoretical. Two aspects are noteworthy in this case. Firstly, materials showing low acoustic impedance have a high value of acoustic attenuation coefficient. Secondly, for technological reasons, materials showing impedance values perfectly corresponding to the calculated theoretical values are difficult to produce. In addition, not all available materials can be used as matching layers in transducers. A solution to the above problems may lie in treating the selection of matching values as an optimisation task. In such an approach, candidate materials for a matching layer should be selected from the available materials so as to optimise a selected parameter describing the quality of the radiation from the transducer to a particular medium (e.g. the transmission coefficient T). The selection of an acoustic matching layer consists then in searching the state-space of possible solutions (in this case, various combinations of materials for the matching layer). When designing a transducer having several matching layers and with a great number of available materials, the search space may be large and the task becomes complex. Solutions to optimisation tasks with large search spaces may involve methods based on artificial intelligence which include genetic algorithms. Publications (Saffar, Abdullah, 2012; Saffar *et al.*, 2014) provide examples of how genetic algorithms are employed in the selection of matching layers for transducers operated in air. The mechanism behind the classical genetic algorithm can be shown as a series of the following steps:

1) An initial population is generated randomly.
2) The population is evaluated (selection). Individuals displaying the best fitness take part in the reproduction process.
3) Genotypes of the selected individuals are subjected to evolutionary operators:
   a) crossover (recombination of the parent genotypes),
   b) mutation (introduction of minor, random changes to the genotypes).
4) Creation of a new generation (new population). If the solution is not satisfactory, return to point 2. Otherwise, a solution is obtained.

Population is understood as a set of individuals having a particular size. An individual is a set of task parameters which are a candidate solution to a problem and which are encoded in the form of chromosomes. In the case of the problem discussed here, its solution comprises such a combination of k matching layers which ensures the optimisation of a particular criterion. As the solution depends on the parameters of the ceramic material used in the transducer and on the parameters of the medium into which energy is radiated, the following structure of the chromosome (individual) can be assumed:

$$o_j = [w_1, (w_2; l_2), \ldots, (w_{n-1}; l_{n-1}), w_n], \qquad (11)$$

where w_i is the index of the material in the i-th layer ($I = 1, \ldots, n$, $n = k + 2$), l_i is the thickness of the i-th matching layer.

Symbol w_1 denotes the ceramic material of the transducer, while w_n is the medium into which energy is radiated. Symbols $w_2 - w_{n-1}$ indicate materials for the searched matching layers, while symbols $l_2 - l_{n-1}$ are thicknesses of individual layers, respectively. In the literature, the thickness of the matching layer is frequently accepted at 1/4 of the wavelength calculated for the frequency of mechanical resonance f_m ($l_i = \lambda/4$ or uneven multipliers of this value). In such a case, the chromosome structure may be simplified in the following form:

$$o_j = [w_1, w_2, ..., w_{n-1}, w_n]. \tag{12}$$

The selection method should ensure that successive populations have a higher average fitness function value. The basic selection method is the roulette wheel method. Despite some disadvantages, it is frequently used in genetic algorithms. In the roulette wheel method, each individual is assigned a proportion of the wheel corresponding to the value of the fitness function for a particular individual (higher fitness function value means larger proportion of the wheel assigned to the individual). The development of evolutionary methods resulted in more effective methods: rank selection method, tournament selection method, etc.

A population resulting from the selection process is then subjected to genetic operators. The goal behind this step is to obtain a new generation which should include better solutions to the problem than the solutions in the previous generation. Two operators are used in a classical genetic algorithm: crossover and mutation. The simplest version of crossover is single point crossover. In this case, a pair of individuals (parents) and a crossover point are randomly selected from the population. The parent individuals are then split in the crossover point (which is identical for both individuals). The first fragments of the individuals (before the crossover point) are not altered, while the remaining fragments of the individuals (from the crossover point) are exchanged (subjected to the crossover operation). This procedure leads to the creation of a pair of two new individuals (offspring). For the structure of individuals described with relationship (12) and for the value of $N = 5$ (3 matching layers are assumed), the crossover operator works as illustrated below. Two individuals, o_{p1} and o_{p2}, were randomly selected from the parent population:

$$\begin{aligned} o_{p1} &= [w_1, w_{12}, w_{13}, w_{14}, w_5], \\ o_{p2} &= [w_1, w_{22}, w_{23}, w_{24}, w_5]. \end{aligned} \tag{13}$$

In the next step, a crossover point equal 2 was randomly selected. As a result, two new individuals (offspring) were created – o_{c1} and o_{c2}:

$$\begin{aligned} o_{c1} &= [w_1, w_{12}, w_{23}, w_{24}, w_5], \\ o_{c2} &= [w_1, w_{22}, w_{13}, w_{14}, w_5]. \end{aligned} \tag{14}$$

The purpose of mutation is to introduce diversity into the new population in order to prevent the loss of important components from the solution. Mutation consists in the change of the value of a selected bit in the string representing an individual. For the structure of individuals described in relationship (12), mutation may consist in a random change of the symbol found in positions 2, ..., $N-1$ (positions 1 and N must remain unaltered). This operation is equivalent to the change of the material in one of the matching layers.

An important element of the genetic algorithm which has a significant influence on its effectiveness is the fitness function. It allows each individual in the population to be evaluated and the results to be used to select the fittest (closest to the optimal solution) individuals for further steps of the algorithm. In this paper, the evaluation of individuals was based on the transmission coefficient T, as defined with relationships (6)–(9).

4. The results of the experiment

The purpose of the experiments is to evaluate the potential of the genetic algorithm for the identification of matching layers for piezoceramic transducers operated in air and in water. An important element of the experiments is to evaluate the influence of attenuation in the matching layers on the obtained results. Therefore, the individuals were evaluated on the basis of the transmission coefficient T, calculated from relationships (6)–(9). An assumption was made that the transducer was manufactured from the PZT ceramic material with impedance $Z_1 = 33$ MRayl. For simplification purposes, the thickness of individual layers was assumed at $\lambda/4$. The experiments were performed on a database comprising 96 available materials with various acoustic properties. The database was developed with the use of data included in a number of scientific articles on designing ultrasound transducers with matching layers and in catalogues from manufacturers of ultrasound materials (ONDA, 2003; HUNG, GOLDSTEIN, 1983; RHEE *et al.*, 2001; ALVAREZ-ARENAS, 2004; TROGÉ *et al.*, 2010; SAFFAR *et al.*, 2014; QIAN, HARRIS, 2014). Table 2 presents some of the materials having various acoustic properties. Figure 4 shows the relationship between the acoustic impedance and the acoustic attenuation for all of the materials from the database used in the experiments. The analysis of the materials included in the database leads to two important conclusions: the database contains a relatively small number of materials with low acoustic impedance, and the materials with low impedance display high values of attenuation coefficient (balsa wood is a good example in this case).

The first experiment consisted in identifying how the attenuation of a material influences the attenuation coefficient in the case of a transducer with one matching layer. The analysis was performed for a transducer operated in air and in water. In the case when the transmission coefficient is optimised, matching layer impedance may be calculated on the basis of the Chebyshev criterion. Optimum impedance value is then 119 kRayl for air and 7036 kRayl for water. The database used in the experiments does not contain ma-

Table 2. Acoustic properties of some materials.

Material	Density [kg/m^3]	Velocity [m/s]	Acoustic impedance [MRayl]	Attenuation [dB/mmMHz]
Nylon	1100	1800	2.00	0.058
Polycarbonate	1220	2270	2.77	0.442
Polyethylene	920	1950	1.79	0.70
Polypropylene	880	2740	2.40	0.10
Polystyrene	1030	2200	2.28	0.17
PVC	1380	2380	3.27	0.224
Teflon	2140	1390	2.97	4.10
Vinyl	2230	1330	2.96	0.256
Paraffin	910	1940	1.76	1.05
TPX-DX845	830	2220	1.84	0.44
Balsa wood	100	800	0.08	22.4
ITAKOM 1	500	1980	0.99	3.0
ITAKOM 2	250	910	0.23	6.5

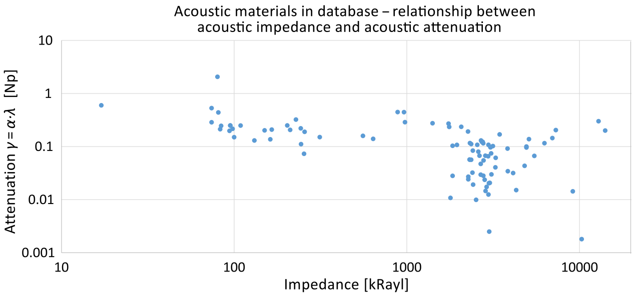

Fig. 4. Acoustic materials in the database.

terials with such impedance. Table 3 presents 5 best results found with the use of the genetic algorithm for each of the criteria. Each of the matching layer materials is provided with its index in the database (value m), as well as its impedance and acoustic attenuation (Z and γ, respectively). The materials were arranged by the obtained value of the transmission coefficient without consideration to the influence of the matching value attenuation (value T_1). Each of the materials is also provided with the value of the attenuation coefficient with consideration to its actual attenuation (value T_2). The obtained results lead to two important conclusions. Firstly, the attenuation coefficient value decreases significantly when the matching layer attenuation is considered (this fact applies especially to air). Secondly, when selecting the material, its attenuation may have a greater importance than its impedance.

The next stage of investigations focused on a transducer with two matching layers. Table 4 includes each 5 best results obtained with the use of the genetic algorithm, for a transducer operated in air. Two cases were considered: one, in which the attenuation of the matching layers was not considered in the calculations of the transmission coefficient (the solution selected on the basis of value T_1), and another one, in which the attenuation was considered (the solution selected on the basis of value T_2). In both cases, each of the solutions was provided with the values of both T_1 and T_2. The analysis of the results indicates that allowing

Table 3. Effect of material attenuation for a transducer with a single matching layer (top 5 results).

Medium (Z_T [kRayl])	Layer 1 m (Z [kRayl], γ [NP])	Transmission coefficient T_1	Transmission coefficient T_2
Air (0.427)	14 (109; 0.249)	0.99276	0.01077
	3 (131; 0.130)	0.99035	0.03283
	2 (100; 0.150)	0.97116	0.02583
	17 (98; 0.216)	0.96414	0.01380
	12 (95; 0.249)	0.95197	0.01072
Water (1500)	90 (6970; 0.145)	0.99991	0.84657
	64 (7300; 0.204)	0.99864	0.79391
	88 (6265; 0.116)	0.98666	0.86273
	87 (5475; 0.067)	0.93965	0.87014
	92 (9150; 0.014)	0.93401	0.91841

Table 4. Effect of material attenuation for the transducer with two matching layers (air, top 5 results).

Medium (Z_T [kRayl])	Layer 1	Layer 2	T_1	T_2
	Without attenuation			
Air (0.427)	86 (4810; 0.043)	22 (17; 0.600)	0.99969	0.05544
	67 (4930; 0.096)	22 (17; 0.600)	0.99821	0.04626
	65 (5100; 0.138)	22 (17; 0.600)	0.99422	0.03973
	93 (4300; 0.015)	22 (17; 0.600)	0.99113	0.07090
	85 (4130; 0.032)	22 (17; 0.600)	0.98204	0.07086
	With attenuation			
	39 (1790; 0.011)	22 (17; 0.600)	0.43888	0.14009
	47 (1840; 0.028)	22 (17; 0.600)	0.45722	0.12957
	43 (2520; 0.010)	22 (17; 0.600)	0.68949	0.12677
	57 (2270; 0.024)	22 (17; 0.600)	0.60928	0.12579
	42 (2420; 0.019)	22 (17; 0.600)	0.65833	0.12463

for the attenuation significantly influences the obtained solutions. The best solution obtained on the basis of the T_2 value (materials 39 and 22) has a low value of coefficient T_1 (0.43888). In reverse, the best solutions obtained on the basis of the T_1 value show a low value of coefficient T_2. The results for a transducer operated in water are shown in Table 5.

The above results demonstrate that the selection of materials for the matching layers of a transducer should be based also on the value of the attenuation coefficient for the particular material. Therefore, in the final stage of the research, investigations focused on how an increased number of matching layers influences the value of coefficient T_2 (with allowance for material attenuation). The considered cases involved from 1 to 4 layers. The results are presented in Table 6. In the case of air, the best result was obtained for two matching layers, and in the case of water – for three layers.

Table 5. Effect of material attenuation for the transducer with two matching layers (water, top 5 results).

Medium (Z_T [kRayl])	Layer 1	Layer 2	T_1	T_2
	Without attenuation			
Water (1500)	92 (9150; 0.014)	46 (1950; 0.107)	1.000000	0.934749
	53 (80; 2.063)	22 (17; 0.600)	0.999989	0.000096
	85 (4130; 0.032)	72 (885; 0.446)	0.999974	0.760768
	55 (14100; 0.200)	83 (3025; 0.021)	0.999961	0.867857
	56 (12900; 0.300)	36 (2770; 0.116)	0.999949	0.758927
	With attenuation			
	63 (10300; 0.002)	60 (2270; 0.027)	0.998901	0.983166
	63 (10300; 0.002)	42 (2420; 0.019)	0.990622	0.979150
	91 (16200; 0.001)	35 (3000; 0.003)	0.980413	0.978420
	63 (10300; 0.002)	43 (2520; 0.010)	0.981293	0.974784
	63 (10300; 0.002)	40 (2400; 0.032)	0.992148	0.973983

Table 6. Acoustic impedances of matching layers obtained with the genetic algorithm.

Z_T [kRayl]	Number of layers	Layer 1	Layer 2	Layer 3	Layer 4	T_2
0.427 (air)	1	5 (254; 0.073)	–	–	–	0.06784
	2	39 (1790; 0.011)	22 (17; 0.600)	–	–	0.14009
	3	93 (4300; 0.015)	5 (254; 0.073)	22 (17; 0.600)	–	0.13419
	4	35 (3000; 0.003)	43 (2520; 0.010)	39 (1790; 0.011)	22 (17; 0.600)	0.13342
1500 (water)	1	92 (9150; 0.014)	–	–	–	0.91841
	2	63 (10300; 0.002)	57 (2270; 0.024)	–	–	0.98461
	3	63 (10300; 0.002)	93 (4300; 0.015)	35 (3000; 0.003)	–	0.98858
	4	63 (10300; 0.002)	35 (3000; 0.003)	43 (2520; 0.010)	39 (1790; 0.011)	0.98582

In the case of air, the transmission coefficient is most influenced by the layer with the lowest impedance (it has a high attenuation value). As mentioned above, due to technological constraints, materials with low impedance have high attenuation. Also, the number of such materials is limited. Importantly, the results were obtained only for a specific set of materials (the database comprised 96 materials). The results may be improved with a larger database.

5. Conclusions

This paper presents a genetic algorithm based method for the selection of materials functioning as matching layers in piezoelectric transducers. The introduction of a genetic algorithm allows the selection of matching layer materials from the available materials so as to optimise a selected parameter related to the transmission of energy from the transducer to a particular medium (this paper has focused on the transmission coefficient T). Depending on the implemented fitness function, the calculations may include various factors related to the selection of matching layers. The research focused on identifying the influence of the acoustic impedance and the acoustic attenuation of matching layer materials on the energy attenuation coefficient for transducers operated in air and in water. The investigated case was a transducer with multiple matching layers (from 1 to 4). The results reveal that the matching layer acoustic attenuation (overlooked in many publications) has a significant influence on the transmission coefficient, especially in the case of a transducer transmitting energy into air.

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