# Novel Impedance Matching Materials and Strategies for Air-Coupled Piezoelectric Transducers.

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***Abstract*—This paper reviews the ideal configuration of air-coupled transducers and compares it with that of actual ones. This reveals the main problems present nowadays in the design and construction of these transducers, consequently, some solutions are proposed: 1. Modification of the selection criteria for the matching layers, with a proposal of a new kind of impedance matching materials and 2. New design strategies to cope with the inevitable non-ideal features present in the design.**

## I. Introduction

The performance of air-coupled piezoelectric transducers is limited by the acoustic impedance ($Z$) mismatch between the air and the piezoelectric material. Although different matching schemes have been intended in the past, the key point is always to have a matching material with a $Z$ and an attenuation coefficient ($\alpha$) as low as possible [1-4].

In spite of these efforts, air-coupled transducers are always designed under non-ideal conditions, being the main one the use of a non ideal outer ML due to the lack of materials that meet the theoretical requirements. Other non-ideal features present in the actual air-coupled transducers are due to the difficulty in putting together the matching layers, to tune them efficiently and to the porous nature of some of the employed materials.

## II. Design Criteria and the Air-Coupled Transducer with an Ideal Matching

The optimization of the ML design has been largely studied before for different applications (e.g. [5] and [6]). In this case, the ideal air-coupled transducer here proposed is based on a stack of quarter-wavelength (λ/4) MLs, where the Z of the *i*-th ML ($Z_i$) is given by:

$$Z_i = (Z_{i-1} Z_{i+1})^{1/2} \quad . \qquad (1)$$

For a *n*-layers stack, $Z_i$ is worked out from the Z of the piezoelectric element ($Z_p$) and the irradiated medium ($Z_M$) by:

$$Z_i = \left( Z_p^{i/n} Z_M^{(n-i+1)/n} \right)^{n/n+1} \quad . \qquad (2)$$

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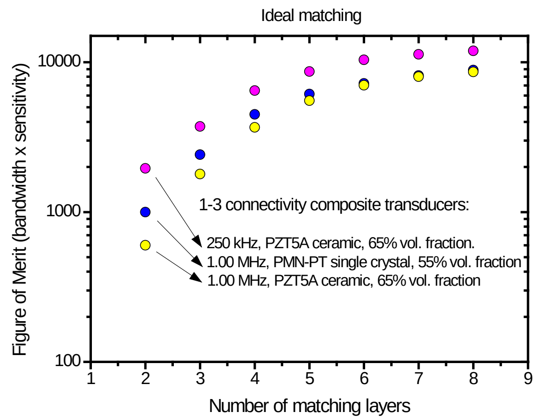


Figure 1. Variation in *fom* with the number of MLs

TABLE I. Properties of the ML for the Air-Coupled Transducer with Ideal λ/4 Matching.

| **Layer** | **Z (MRayl)** | **Thickness (λ/4) (µm)** | |
|---|---|---|---|
| | | **0.25 MHz** | **1.00 MHz** |
| 1 | 0.0014 | 37 | 9 |
| 2 | 0.0044 | 66 | 16 |
| 3 | 0.0139 | 118 | 29 |
| 4 | 0.0441 | 210 | 52 |
| 5 | 0.1400 | 373 | 93 |
| 6 | 0.4420 | 664 | 166 |
| 7 | 1.4000 | 1182 | 295 |
| 8 | 4.4200 | 2103 | 525 |

In this paper, we study the transducer performance in transmission + reception mode (*Tx*-*Rx*). This may correspond to pulse-echo or pitch-catch operation modes when *Tx* and *Rx* transducers are identical. The proposed figure of merit (*fom*) is derived from the conventional gain-bandwidth product [7]. Gain obtained as maximum peak to peak signal amplitude in the time domain for a given *Tx* excitation conditions; and the bandwidth measured at -20 dB of the maximum value. Transducers response is calculated for two different piezoelectric 1-3 connectivity composites: PZT5A fibers and PMN-PT single crystal pillars, and for two different frequencies: 0.25 MHz and 1.00 MHz. [8] As an example, Fig 1 shows the variation in *fom* with the number of MLs in the transducer. Optimum *fom* is achieved for eight MLs. All layers have a λ/4 thickness and $Z_i$ are calculated by Eq. (2). Table I summarizes the main properties, thicknesses are calculated assuming $v = C\,\rho$, where $C \approx 1$ (m$^4$ s$^{-1}$ kg$^{-1}$).

Fig. 2 shows the calculated response of a 1.00 MHz transducer made with a 1-3 connectivity PZT5A ceramic composite (65% vol. fraction) and with the ideal matching configuration that provides the optimum *fom*: 8 MLs. Both sensitivity and bandwidth of this transducer are remarkable, however its realization is nowadays impossible for a number of reasons that are explained in the next section.

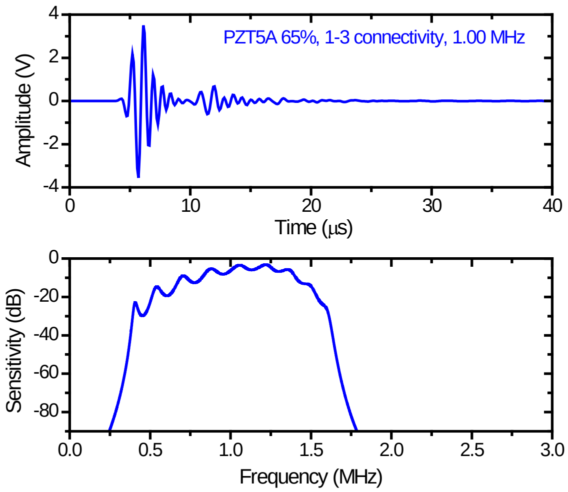


Figure 2. Calculated response (Tx-Rx). Ideal stack of 8 λ/4 MLs

## III. Non-ideal features of actual air-coupled piezoelectric transducers.

### *A. Matching layers impedance*

In general, the more important design restriction is the impossibility to fabricate impedance MLs with the required very low Z value (see Table I). The lowest attainable Z value for a ML depends on the frequency (*f*). At present, these limits are between 0.01 MRayl ($f < 200$ kHz) and 0.05 MRayl ( $f < 1.00$ MHz). Therefore, actual outer MLs have not the ideal Z value given by Eq (2), but a value which is determined by the availability of materials. Once the properties of the outer ML has been determined, the required Z of the intermediate ML is worked out using Eq. (3) [9].

$$Z_i = \left(Z_p^{i/n} Z_n^{(m-i+1)/n}\right)^{m/m+1}, \qquad (3)$$

where m= n-1. The consequences of having a non-ideal outer ML are illustrated in Fig. 3 for one particular case. It shows the variation of *fom* with the number of MLs assuming a fixed value in the Z of the outer ML ($Z_n$). Now the maximum number of MLs that can be used is reduced and there is a significant decrease in the *fom.*

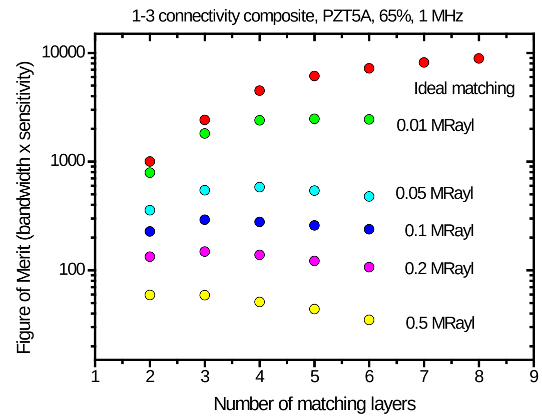


Figure 3. Variation in *fom* with the number of matching layers for a given value of $Z_n$

### *B. Matching layers thickness*

Fabrication, handling and mounting of a low Z film with thickness as low as those in Table I can be extremely difficult. In addition, for Z < 0.7 MRayl, MLs must bee made of porous materials. In such cases, pore size ($a_p$) must be much smaller that the layer thickness (*t*) -approximately $a_p < t/100$-. This imposes an additional restriction on the maximum acceptable pore size which further limits the range of suitable materials.

### *C. Matching layers mounting*

Some of the MLs cannot be fabricated directly on the transducer surface but have to be fabricated separately and then attached to it. This can be done by a thin layer of glue (resin, elastomer, etc.) or adhesive tape. The *Z* of this layer normally varies from 0.8 to 2.4 MRayl and the thickness is, typically, in the range between 100 and 10 µm, depending on the method to apply it: spray coating, spin coating, deep coating, etc. Depending on the properties of the MLs to be attached together, the presence of this adhesive may suppose the insertion of an undesired layer of relatively high Z.

### *D. Open porosity in the matching layers.*

For $Z < 0.3$ MRayl materials normally present an open-pore porosity. In such cases, attaching together the MLs can be difficult. Use of adhesives must be limited because they may penetrate into the porous structure and modify the its acoustic properties [3]. In addition, open-pore porous materials do support two different longitudinal propagation modes [10]. Under some circumstances they correspond to the propagation in the fluid filling the pore space and in the porous skeleton. MLs made of porous materials are designed to operate using the porous-skeleton borne wave, however, the pore-space borne wave has also been observed in materials similar to those used to produce matching layers [11]. Though pore-space borne wave is normally not observed because it is highly attenuated, mode conversion always take place at the layer interfaces, this may produce a significant deviation of the acoustic energy into an undesired and highly attenuated mode which may reduce the efficiency of the ML. This can be prevented by sealing the pores at the interfaces [12].

### E. *Matching layers tuning.*

Thicknesses of the MLs have to be tuned to the transducer centre frequency, however many of the materials used for this purpose (polymeric membranes, fibrous porous composites, aerogels) cannot be machined down to the right thickness because they are either too soft or too brittle. Therefore, they have to be fabricated with the right thickness, however, this is not always possible. This can be avoided by using rigid non-brittle machinable foams.

## IV. Novel Criterion for the Selection of the Matching materials.

Materials selection has been conventionally performed based on the material impedance; later, the criterion of material attenuation was introduced. $Z$ is obtained from the velocity ($v$) and the density ($\rho$) by: $Z = v\,\rho$.

However, no attention has been paid before to the actual value of these two factors. Our proposal here is to use $v$ as additional design criterion so that for two materials having the same value of $Z$, the one with the larger velocity must be preferred. There are four main reasons to set this criterion, as materials having a larger velocity value also present: 1. smaller attenuation, 2. larger ML thickness 3. larger acceptable pore size. 4. more closed-pore structure, and layers with closed pores are more easily attached together and to the transducer and do not support the pore-space borne wave.

According to Ref. [13], the relative Young modulus ($E^*/E_s$) for open pore and closed pore cellular solids or foams is given by Eqs (4) and (5), respectively

$$E^*/E_s \approx (\rho^*/\rho_s)^2 \tag{4}$$

$$\frac{E^*}{E_s} \approx \phi^2\left(\frac{\rho^*}{\rho_s}\right)^2 + (1-\phi)\frac{\rho^*}{\rho_s} + \frac{\rho_0(1-2\nu^*)}{E_s(1-\rho^*/\rho_s)} \tag{5}$$

where * and s denote the cellular structure and the solid constituent, respectively, ($1-\phi$) is the fraction of solid which is contained in the cell faces and $\upsilon$ the Poisson's ratio. The main reason for the different mechanical behavior is due to the thick cell face that closes the pores to form isolated cells [13].

Therefore, there are two ways to produce a cellular solid with a given Z value but with a relatively larger velocity: 1. to select solids with relatively larger $E_s$ and lower $\rho$ to fabricate the cellular material (rigid polymers are preferred over elastomers, ceramics or metals) 2. to use fabrication routes that enhance the generation of closed-cell pore structures. These two alternatives are illustrated in Figure 4, where the calculated variation in Z with the velocity according to Eqs. (4) and (5) for several values of $E_s$ (from 0.4 to 5 GPa) and for the two possible structures (open- and closed- cell) is shown, assuming that the Poisson's ratio is 0.33 [13]. For a given Z value, the larger the $E_s$ is, the larger the obtained velocity, and for a given Z and a given $E_s$, the more closed the pore structure is, the larger the velocity. This later fact is specially significant at low Z values.

Fig. 4 also shows measured values for a large set of materials that have already been either used or proposed: cellulose nitrate, polyethersulfone, nylon, polypropylene, and polyolefine membranes, non-woven fiber composites (including paper), vegetable tissues (including balsa wood and other lightweight woods), and granular composites like silica aerogels and mineral paper. In spite of the different solid constituents, porous structures and pore sizes the variation in Z with the velocity can be well described by Eq (4) (open-cell cellular solid) with $E_s$ values between 0.4 and 2.4 GPa. It is important to point out the fact that the actual value of $E_s$ is rarely known. For natural materials because the actual composition of the solid is not known and for polymeric foams because it depends on the degree of polymer chain alignment and the chemical influence of foaming agents.

Finally, Fig 4 also shown the measured values for the new set of proposed material: a rigid polymer foamed under conditions to preserve the large $E_s$ (5 GPa) value of the polymer and to enhance the presence of closed pores.

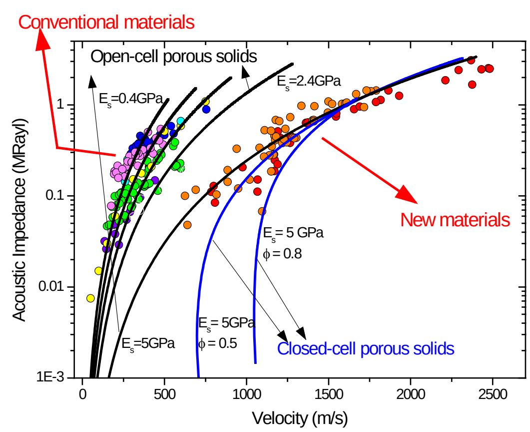


Figure 4. Experimental (dots: green: polymeric membranes, blue: paper, yellow: silica aerogels, pink: vegetal tissues, marine: flexible foams, red and orange: new rigid semiclosed-cell polymeric foms) acoustic impedance versus ultrasound velocity and theoretical values according to Eqs. (4) and (5) for several values of the Young modulus of the solid and for two different porous structures: open-cell and closed cell.

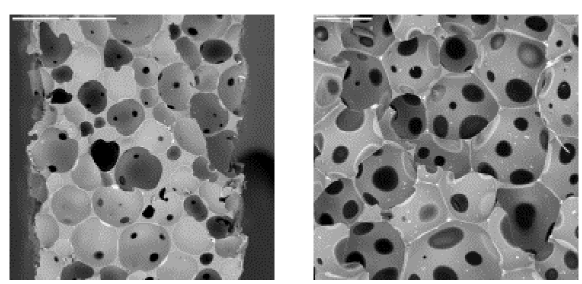

Figure 5. SEM images of cross-sections of two of the cellular rigid solids proposed as low *Z* and high *v* matching layers

These new materials effectively achieve low Z values (down to 0.05 MRayl) while keeping a relatively large velocity (>640 m/s), about 3 times larger than that of conventional materials used for this purpose. Figure 5 shows two SEM images that reveal the typical pore structure of these materials. In addition, they present two additional advantages: 1. Attenuation is very low (<100 Np/m @ 1 MHz, while conventional materials present attenuation values between 500 and 1500 Np/m); 2. This material can be easily machined to precisely tune the ML thickness to the desired frequency.

## V. Novel Desing.

To cope with the non-idealities present in the transducer design previously explained, the following design procedure is proposed. First, the material to produce the outer ML is selected and then the number of matching layers is determined according to the procedure in Fig. 3. Then Z of the intermediate MLs is calculated (Eq. 3). This provides the initial solution. This initial solution is optimized by simultaneously varying thickness and Z of each of the intermediate MLs, from 50% to 150% of the initial value in 10% steps. At each step, the value of the *fom* for the Tx-Rx configurations is calculated and the configuration that provides best *fom* is selected. The calculations were implemented in a MATLAB routine. Run time largely depends on the number of matching layers to optimize.

Therefore, the final transducer design does not comprises a set of ideal λ/4 matching layers whose Z value is calculated by Eq. 3; instead of this, the new design introduces some variations in both Z and thickness of the MLs that are intended to compensate the non-ideal features present in the transducers, mainly those linked with the presence of adhesive layers and with the lack of proper ML materials.

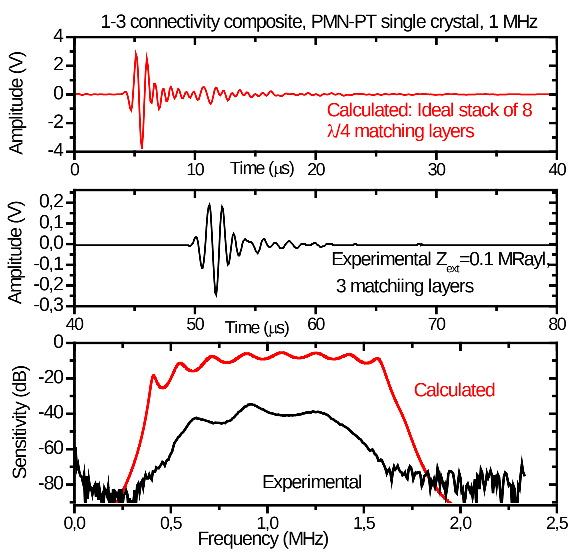


Figure 6. Theoretically calculated response (Tx-Rx) of the air-coupled transducer with an ideal stack of λ/4 impedance matching layers and measured response (Tx-Rx) of the prototype built with the novel proposed materials and design procedure.

## VI. Experimental Results.

As an example of the results that can be obtained, Fig. 6 shows the measured *Tx-Rx* response of a 1 MHz transducer made using a 1-3 connectivity PMN-PT single crystal piezocomposite, and a stack of three MLs designed and built using the proposed materials and procedures. Transmitter is driven by a PANAMETRICS 5077 (200 V semicycle), gain in reception is set to 0 dB and Tx-Rx separation was 17 mm. Results are compared with those theoretically obtained with an ideal stack of 8 MLs.

## VII. Conclusions

Air-coupled piezoelectric transducers can be improved by using a new kind of ML materials based on rigid polymer foams (relatively larger velocities, almost closed-pore structure, machinable, low *Z* and low *α*) and a new design procedure that allows the MLs to deviate from ideal *Z* and *t* values to cope with non-idealities present in the transducer (e.g. adhesive layers between ML, non-ideal *Z* value of the ML, etc.). This constitutes a more flexible fabrication procedure that yields transducers with a similar sensitivity but with a larger and smoother frequency band, compared with previous solutions.

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