# MODELING AND EVALUATION OF DISTINCT ALTERNATIVE DESIGNS FOR WIDE-BAND AIR-COUPLED PIEZOELECTRIC TRANSDUCERS

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## ABSTRACT

Air-coupled ultrasonic piezoelectric transducers have demonstrated their usefulness in several areas such as materials characterization, surface metrology, or NDE. Although sensitivity is good, their bandwidth is quite narrow. This can be improved by adding two or more matching layers. Usually, these layers become unpractical because they either extremely thin, or light or brittle and such transducers have to be constructed using materials that are far from the ideal specifications. Here, a comprehensive modeling tool (PSPICE) for the design of air-coupled piezoelectric transducers with improved bandwidth, considering real and low attenuating materials is presented. Several characteristic broadband functions, were simulated in time-frequency domains, for selected sets of the piezoelectric and matching layer materials. Finally, the best transducer design considering real materials within the double-matching layer scheme is proposed. The analysis is restricted to transducers having a centre frequency at 1 MHz. The simulated transducer performance is compared with experimental data.

Keywords: air-coupled transducer, matching layer, PSPICE, material properties.

## 1. INTRODUCTION

The application of air-coupled ultrasonic devices have achieved a notable impetus during the last years. This has been demonstrated in different areas such as environment protection, health care or Non Destructive Testing (see Grandia and Fortunko 1995 for an early review) .

Air-coupled piezoelectric transducers show a good sensitivity, but their bandwidth is narrower compared with electrostatic devices (Hutchins and Schindel 1994). An important application of air-coupled ultrasounds is for the study and characterization of materials that can not be wetted (as it is usually done in conventional ultrasonic techniques for they require the use of coupling fluids between transducer and samples) (Fortunko, Renken and Murray, 1990, McIntyre, Hutchins, Billson and Stor-Pellinen, 2001, Gómez 2002, Gómez 2003a, Gómez 2003b, Gómez, Apel and Orelovitch 2007). It will be an important advantage, especially for these spectroscopic applications if present bandwidth can be further improved.

These piezoelectric devices require the use of impedance matching layers to partially reduce the huge impedance mismatch between the air and the piezoelectric materials. In some cases, use of these layers is quite hard because they are either extremely light, brittle or thin. Therefore, such transducers have to be constructed using real materials that are far from the ideal specifications (Gómez 2004).

Taking into account these limitations, specific modelling and simulation tasks of different transducers design configurations, are needed. Afterward, these tasks can conduct to a more proper and complete transducer prototyping.

Therefore, the objective of this work is to develop and check a modelling tool (based on PSPICE) for the search of improved transducer configurations. This tool is verified by comparing the modelled transducers response with the experimentally measured one for the case, already known, of a design based in the use of two quarter-wavelength matching layers. In addition, the response of an ideal transducer (i.e. a transducer having two matching layers whose impedances are exactly those theoretically calculated) is also modelled. This provides a reference to compare the performance of transducers produced using real materials.

## 2. TRANSDUCER DESIGN

A wideband air-coupled piezoelectric transducer can be represented by a multi-element structure. Figure 1 presents the diagram of an air-coupled transducer design with two matching layers, no backing and mounted on aluminium housing. This comprises of a piezoelectric ceramic (the active element of the structure where the electro-mechanic energy conversion takes place), and the matching layers, which allow a more efficient transmission of the ultrasonic wave to the propagation medium. Additionally, other elements can be considered in the design depending of the requirements demanded by the transducer specific application, (for example, one element added to the piezoelectric ceramic rear face and named “backing”).

The enormous impedance mismatch between piezoceramics (≈30 MRayl) and air (≈0.0004 MRayl) has two important consequences for the design of air-coupled transducers: sensivity is very low (~ -60 dB ) and bandwidth is quite narrow (~ 5%). Sensivity can be improved by a single matching layer, but widening the frequency bandwidth requires the use two or more matching layers. The selection of the suitable matching layer materials is a key issue.

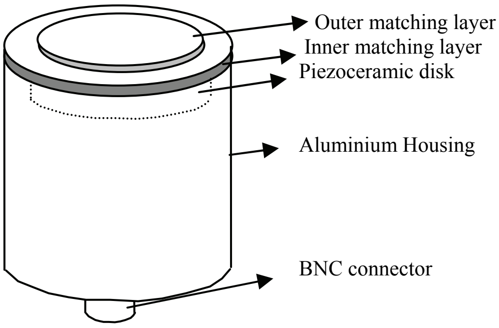


Figure 1. Diagram of the two-matching layers air-coupled transducer design.

Aditionally the thickness of the layers is a critical factor and several matching configurations have been proposed (Kelly, Hayward, and Gómez 2004, Gómez 2004, Toda 2002). In any of these matching configurations, a key aspect for the successful design is the acoustic impedance of outer layer. This is highly limited by the availability of suitable materials having the very low specific acoustic impedance, very low attenuation, and the required thickness for the designed configuration and working frequency.

The optimum acoustic impedance of the quarter wavelength layer can be obtained by the following expression:

$$Z_l = \sqrt{Z_1 Z_2} \quad (1)$$

where $Z_l$ is acoustic impedance of the matching layer. $Z_1$ and $Z_2$ are the acoustic impedance of the piezoceramic and the air respectively.

For a stack of matching layers, the equation (1) can be generalized and the impedance of successive layers to be added can be also obtained.

An analysis of a group of the more proper materials for the construction of the matching layers at 1 MHz was done. Table I summarizes the properties required by the simulation model of some candidate materials to produce quarter wavelength matching layers to match piezoelectric transducers to the air using a two-layers scheme. In Table I *Z* is the specific acoustic impedance, $f_r$ is the quarter wavelength resonant frequency and $\alpha$ is the attenuation coefficient. The polyurethane, the epoxy resin and the silicone rubber listed in Table I can be used as the first or inner matching layer, while the membranes in Table I can be used as the second or outer matching layer. Membrane materials, unlike the other available materials, are only available at certain grades and thicknesses, hence, for a given membrane material and grade $f_r$ is fixed and can not be changed. The only way to obtain a different $f_r$ is to change the grade, the material or the vendor (Gómez 2003a and 2003b)

The properties of the selected materials were analyzed and considered for the realization of distinct transducer design alternatives, including one or two matching layers. This analysis was complemented with modelling and simulation tasks of different transducer design options evaluated inside a selected practical transceiver configuration.

Table I. Materials properties

| Material | $Z$ (MRayl) | $f_r$ (MHz) | $\alpha$ at $f_r$ (Np/m) |
|---|---|---|---|
| Polyurethane | 2.25 | 1.00 | 45 |
| Epoxy resin | 2.80 | 1.00 | 40 |
| Silicone Rubber | 1.35 | 1.00 | 45 |
| Nylon membrane (1) | 0.11 | 1.00 (*) | 270 |
| Polyethersulfone membrane (1,2) | 0.25 | 1.20 (*) | 200 |
| Cellulose Nitrate (1,2) | 0.25 | 1.00 (*) | 400 |
| Cellulose Nitrate (3) | 0.12 | 0.7 (*) | 680 |

1: Gómez (2003a)
2: Gómez (2004)
3: Kelly, Hayward, and Gómez 2004.
*: Frequency is given thickness and membrane grade. They can not be changed to tune the resonant frequency.

## 3. ULTRASONIC TRANSCEIVER MODEL

A through-transmission (T-T) configuration was considered in order to simulate the performance of the different design alternatives. This transceiver configuration was implemented in a circuit analysis program (PSPICE). Figure 2 presents the electric diagram of the pulsed T-T arrangement, used in the simulation process.

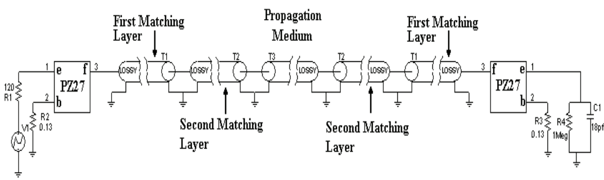


Figure 2. Electrical diagram of the Through-Transmision configutation.

The piezoelectric stages were modeled using a PSPICE implementation, of a well-known equivalent circuit [Redwood 1961], and which included a quadratic frequency dependence of the mecanical losses in the piezoceramic material [Ramos A., Ruíz A., San Emeterio J.

L., Sanz P.T., 2006]. The three port blocks (PZ27), symbolize the emitting-receiving probes, constructed from piezoceramic PZ27 (Ferroperm piezoceramics a/s). Pins e, b and f denote respectively the electrical and mechanical (back and front) ports of the transducers. Additionally, the matching layers were modelled employing lossy transmission lines using the corresponding material acoustical properties as input data [Van Deventer J., Torbjörn L., Jerker D., 2000].

The electronic driving stage was modelled by a pulsed source and a resistor, and considering the practical driving conditions employed. The receiving electronic included, some elements which symbolize the input impedance of the oscilloscope used. Figure 3 presents the driving electrical signal provided by the pulse source for the experimental measurements. This was generated by a Panametrics 5077 pulser/receiver. This is one half negative cycle of a square wave. The width of the pulse is tuned to provide a maximum energy output at the transducer centre frequency (1 MHz in this case). A similar signal was used for modeling purposes.

For all cases it was considered that the transmitter transducer was very similar to the receiver transducer and that they were separated by an air gap 5 cm thick.

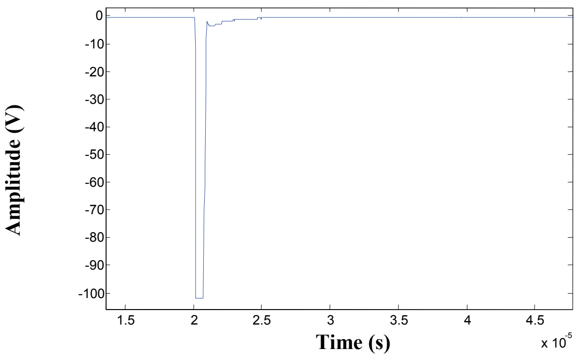


Figure 3. Electrical signal provided by the pulse source.

## 4. RESULTS.

### 4.1. Modelling of the ideal transducer response.

The performance of distinct design alternatives is analyzed by means of the transceiver characteristic broadband functions, such as through-transmission response in time and frequency domain. Among the different design options evaluated, we first considered the employment of matching layers with ideal materials, in order to achieve a reference. This reference was used to evaluate the results obtained with realistic configurations using real materials that present attenuation and whose impedance values do not exactly coincide with the theoretically required value.

This ideal case consists of a piezoceramic layer made of PZ27, with thickness resonant frequency located at 1 MHz. We also considered that matching layers were perfectly tuned to this frequency. For the case of one ideal and lossless quarter-wavelength matching layer the acoustic impedance (according to Eq. 1) takes the value of 0.11 MRayls. For the case with two ideal and lossless quarter-wavelength matching layers, the first or inner matching layer has an acoustic impedance of 0.73 MRayl while the second or outer matching layer has an acoustic impedance of 0.0017 MRayl. It is worthwhile to consider the fact that while for the one matching layer configuration it is possible to find some solid materials having an impedance close to the theoretically required value (at the cost of a non-negligible attenuation), there are not any known solid material with such a low acoustic impedance value as required by the outer matching layer in the two layers configuration.

Figure 4 presents the comparison of the simulated Through-Transmission (T-T) Frequency Response considering different design alternatives in the frontal face of the air-coupled transducer. The solid curve represents the (T-T) response without matching layer in the frontal face of the transducer and the dashed and dotted curves, with one and two matching layers, respectively. The ripple observed at low frequencies is produced by the signal reverberations produced within the air gap. A notable increment of the amplitude can be observed for both cases were a matching layer was used, respect to the case without matching layer. Additionally, a significant bandwidth increment is observed for the two-matching layer option.

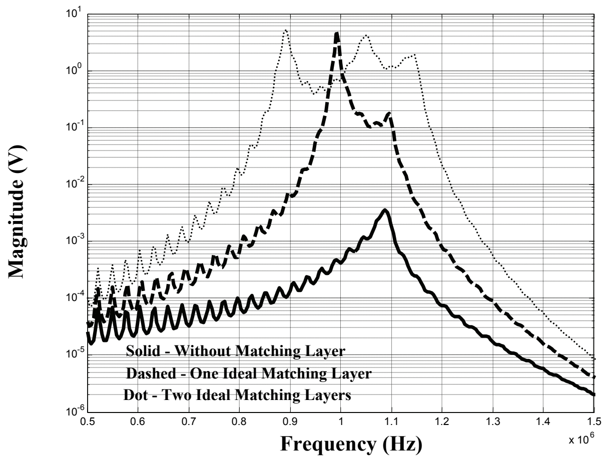


Figure 4. Through-Transmission Frequency Response considering different design alternatives in the frontal face of the air-coupled transducer. Solid: Transducer without matching layer. Dashed: Transducer with an ideal matching layer. Dotted: Transducer with two ideal matching layers.

### 4.2. Modelling of the best possible transducer using real materials and comparison with a practical realisation.

As a second step we consider the problem of transducer design using real materials. A list of some of the candidate materials was presented in Table I. The more successful results in the distinct simulation options evaluated were obtained with the polyurethane and the nylon membrane. According to this, two identical prototype transducers made of PZ27 piezoceramic and two quarter-wavelength matching layers (polyurethane and nylon membrane) were built. The transducer response is both measured and modelled at three different stages: 1. before attaching any matching layer, 2. after the attachment of the first (or inner) one but before attaching the second (or outer) one, 3. after both matching layers have been attached. This is useful for the control of the fabrication process, because in this way the integrity and correct functioning of each matching layer can be determined.

In Figure 5 the Simulated Through-Transmission Temporal Response considering different design alternatives in the frontal face of the air-coupled transducer, for the selected optimum design, employing real and low attenuating materials, is presented. In this Figure we can clearly appreciate the through transmitted signal from the transmitter to the receiver (this is the signal that arrives first) and also the first reverberation within the air gap. As the distance between transducers is 5 cm, this reverberation appears about 300 μs later than the through transmitted one. A bigger amplitude in the (T-T) waveforms is observed with the addition of one and two matching layers in the frontal face of the piezoceramic.

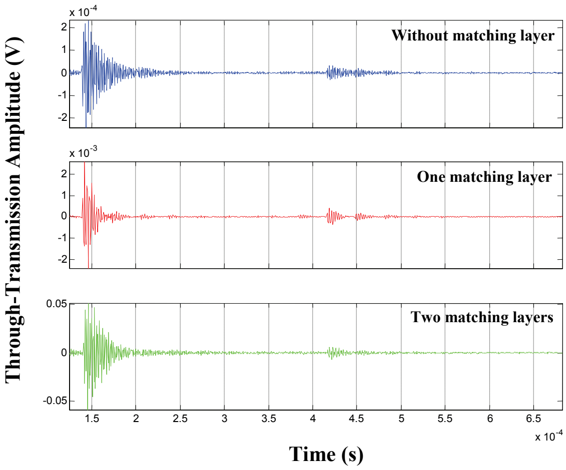


Figure 5. Simulated Through-Transmission Temporal Response considering different design alternatives in the front face of the air-coupled transducer, for a selected optimum design employing real and low attenuating materials. Blue: Transducer without matching layer. Red: Transducer with a matching layer. Green: Transducer with two matching layers.

Then a pair of transducers following this specifications (i.e. PZ27 piezoceramic and two quarter-wavelength matching layers, the first made of polyurethane and the second of nylon membrane) were built. Figure 6 shows a picture of one of them.

Figure 7. shows the experimentally measured Through-Transmission Temporal Response. In this case, separation between transmitter and receiver was 2 cm. The transmitter transducer was driven by the electrical pulse shown in Figure 3, the electrical signal generated at the receiver transducer were digitized and stored using a digital oscilloscope (TDS 5052). As observed in the simulation, the pulse amplitude increases notably with the addition of matching layers. In this case, the first reverberation within the air gap between transducers is also observed, though only about 120 μs later than the through transmitted signal, because the air gap length is smaller (2 cm).

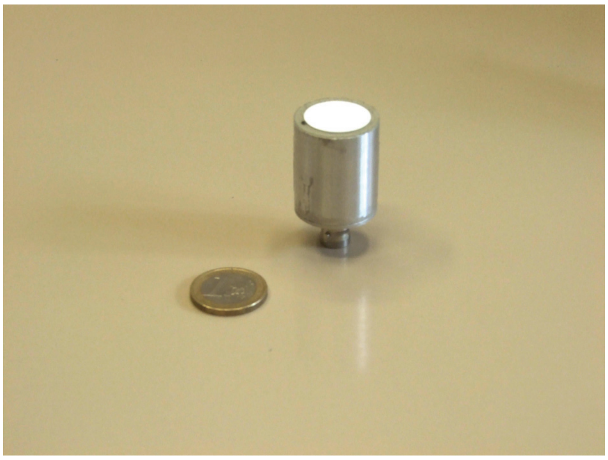

Figure 6. Picture of the air-coupled piezoceramic transducer constructed according to the proposed design i.e. with two matching layers in the frontal face).

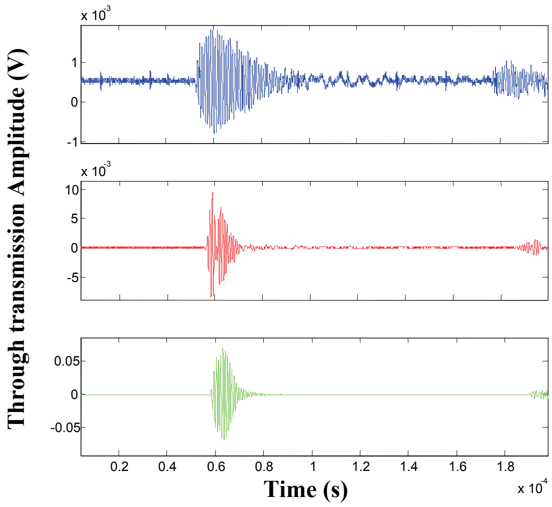


Figure 7. Measured Through-Transmission Temporal Response for several transducers configurations. 2cm separation air gap. Blue: Transducer without matching layer. Red: Transducer with a matching layer. Green: Transducer with two matching layers.

Simulated and experimental Through-Transmission (T-T) Frequency Responses (for the cases presented in Figure 5), can be observed in Figure 8. The theoretically calculated response shows the low frequency ripple mentioned before due to the signal reverberations within the air gap. This is not observed in the experimental data because a rectangular temporal window was applied to the signal to filter out these reverberations before the FFT is calculated. It is possible to appreciate bigger amplitude and bandwidth in the design alternatives with one and two matching layers respectively with respect the no matching layer option. Although the one layer option increases the transducer performance, it is further improved by the addition of a second matching layer. In general, the resonances experimentally observed are not so sharp as those theoretically predicted. This is due to possible imperfections of the layers (i.e. lack of homogeneity or flatness) and also to the possible contribution of the layer of glue used to attach the nylon membrane to the polyurethane layer.

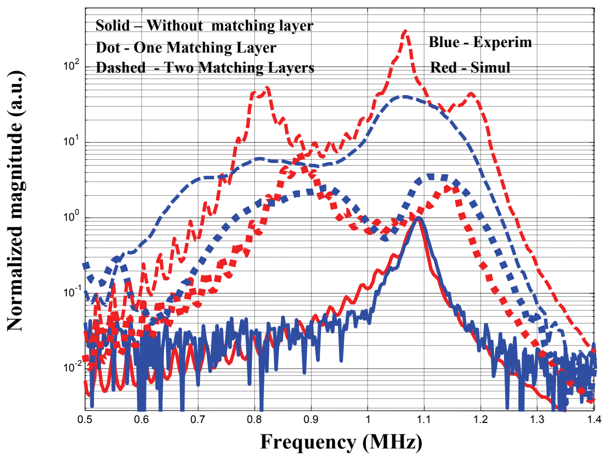


Figure 8. Comparison of the simulated (red color) and experimental (blue color) curves of the Through-Transmission Frequency Response, for different design alternatives in the frontal face of the air-coupled transducer. Solid: Transducer without matching layer. Dashed: Transducer with and ideal matching layer. Dotted: Transducer with two ideal matching layers.

### 4.3. Modelling of the influence of the impedance of the backing material.

The temporal pulse length emitted by the transducer is influenced by the characteristics of the backing element. The backing is usually a a highly attenuative, high density material that is used to control the vibration of the transducer by absorbing the energy radiating from the back face of the piezoceramic. This pulse length is closely related with the bandwidth as the shorter the pulse duration (or length) is, the larger the bandwidth of the transducer. Therefore a way to enlarge the frequency bandwidth of a transducer is to introduce a backing or to employ a material having larger acoustic impedance. This bandwidth enlargement is performed at the cost of reducing the sensitivity of the transducer. As sensitivity is a key issue in air-coupled transducers the suitability of this approach will be determined by the exact trade off between bandwidth enlargement and sensitivity decrease. To study this effect, the model developed and tested in this paper is especially useful.

In this case, we study the selected optimum design, employing real and low attenuating materials for the matching layers in the front face of the piezoceramic (see previous sections) together with three different backing options: no backing (original solution), 2 MRayl backing, and 7 MRayl backing. The second alternative (2 MRayl) corresponds to a light backing material, this can be achieved by using a silicon rubber. The third option (7 MRayl) corresponds to a heavy backing that can be achieved by using an epoxy resin loaded with tungsten powder.

Results are shown in Figure 9. This Figure presents a comparison among the Simulated Through-Transmission Temporal Responses considering the three different design alternatives in the rear face of the air-coupled transducer mentioned above. A shorter pulse length in the (T-T) waveforms can be observed with the addition of a backing, in the rear face of the piezoceramic. As mentioned above this pulse reduction is concomitant with a bandwidth enlargement. A clear reduction of the sensitivity (signal amplitude) is also observed. However in order to determine the best optimum backing impedance it is necessary to consider the application the transducer is intended for. In some cases (i.e. inspection of highly attenuating or difficult to penetrate materials) transducers sensitivity is the main design criteria, while for other cases (spectral analysis– Gómez 2003b and 2007-, study of dispersion relations – Gómez, de la Fuente and González-Gomez 2006 and Gómez and González-Gomez 2007-, axial resolution, search of thickness resonances, Gómez 2003a and 2003b, ), the key issue is the bandwidth of the transducers.

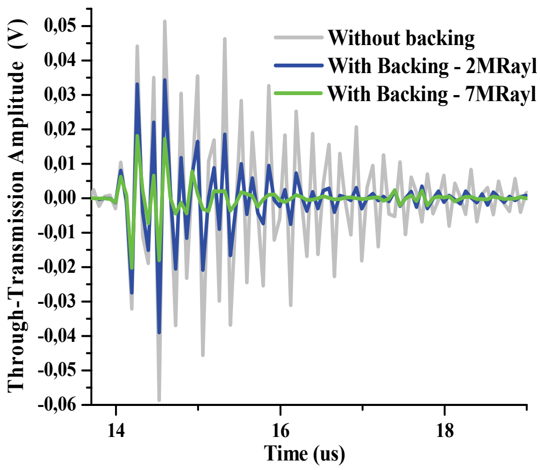


Figure 9. Simulated Through-Transmission Temporal Response considering different design alternatives in the rear face of the air-coupled transducer, for a selected optimum design employing real and low attenuating materials for the frontal matching layers. Black: Transducer without matching layer. Blue: Transducer with a backing of 2 MRayl. Green: Transducer with a backing of 7 MRayl.

## 5. CONCLUSIONS

A new approach to model air-coupled piezoelectric transducers with improved bandwidth and only considering real and low attenuating materials, is presented.

This model has been used to determine the best configuration for a 1 MHz air-coupled transducer based on a PZ27 piezoceramic and only considering real materials to produce matching layers. Configurations based on one and two quarter-wavelength matching layers has been studied. The result of this study is a transducer configuration based on a double matching layer made of polyurethane and nylon membrane. In addition, the performance of ideal air-coupled transducers using ideal matching layers has also been modelled. This provides a reference value in order to compare the performance of real transducers. Finally, the utility of the use of different backing materials has been modelled in order to determine the possibility to further increase the bandwidth of the proposed solution.

According to the model predictions, a pair of prototype air-coupled transducers was built. The model predictions have been compared with the experimentally measured performance of the prototype transducers. This provides an initial verification of the model capability.

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