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Tapered transmission line technique based graded matching layers for thickness mode piezoelectric transducers

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Abstract — **Conventionally, in order to acoustically match thickness mode piezoelectric transducers to a low acoustic impedance load medium, multiple quarter wavelength (QW) matching layers are employed at the front face of the device. Typically a number of layers, 2-4 in number, are employed resulting in discrete impedance steps within the acoustic matching scheme. This can result in impedance matching with limited bandwidth characteristics. This paper investigates the application of tapered transmission line filter theory to implement a graded impedance profile, through the thickness of the matching layer scheme, to solve the impedance mismatch problem whilst accounting for enhanced transducer sensitivity and bandwidth.**

Keywords— **Acoustic transducers, graded matching layer, impedance matching, photopolymerisation, transmission line**

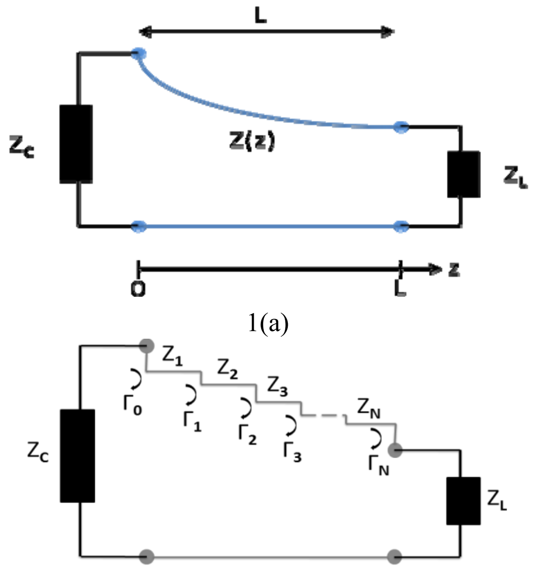
I. INTRODUCTION

PIEZOELECTRIC devices convert mechanical stress to electrical charge or voltage (direct effect), and vice versa (indirect effect). The piezoelectric property can be found in many materials (such as quartz, Lead Zirconate Titanate, and Polyvinylidene Fluoride) and finds a wide range of application in many fields including SONAR, bio-medicine, non destructive evaluation and industrial process control. Typically, piezoceramics (with high acoustic impedance around 30 MRayl) are often used as a active material in such transducers, and using such devices in low impedance loads such as water or human tissue (approximately 1.5 MRayl) will make the device usable only in a very narrow band of frequencies due to the mechanical mismatch. Consequently, matching layers whose acoustic impedance is intermediate between the ceramic and the load medium are used to improve device sensitivity, while operating into such low acoustic impedance loads. Designing matching layers will greatly increase the operational bandwidth and efficiency of a transducer and has to be considered carefully at any design stage. This paper investigates an analogue filter technique based approach to design and optimise graded matching layers for conventional thickness mode piezoelectric transducers.

Firstly, the theory to calculate the reflection/transmission coefficients of a tapered impedance profile is presented. Examples include, but are not limited to, exponential, and triangular taper profiles. Secondly, matching layers with a broad range of acoustic properties for application in piezoelectric probe assemblies are manufactured using a methodology based on photopolymerisation of epoxy resins. The photopolymerisation allows for the rapid fabrication of polymer materials by successive photocuring of thin layers of polymer. The method is elegant in implementation, since the layers can be readily deposited directly onto the front face of the transducer element, eliminating additional bond lines. Indeed, by employing different monomers and dispersing particles into the monomers prior to polymerization, a stratified structure can be produced with the desired acoustic impedance profile. Finally, experimental results are presented in order to demonstrate the effectiveness of this approach – device fractional bandwidths around 80% are demonstrated, for a nominal 1MHz thickness mode transducer design.

II. TAPERED TRANSMISSION LINE THEORY

Several authors have proposed different methods for calculating optimum values for intermediate acoustic matching layers and hence overcome the impedance mismatch problem. Notably, Lewis [1] and Desilets [2] used multiple matching layers, with each layer impedance being a fixed percentage lower (or higher) than the preceding one. Also, multiple QW transformers using analog filter techniques such as Chebyshev (type I and II) and Binomial transforms, have been studied in depth for many years for electrical impedance matching problems [3]. The suitability of applying similar filter design methods to the problem of acoustic matching has been reported by the authors [4-6]. Unlike multi-section matching with discrete QW sections, the impedance can be continuously tapered to achieve broadband matching. Figure 1 illustrates schematically a tapered transmission line used to match an input impedance (i.e. composite transducer, Z_C) to a low impedance water load (Z_L).



1(a)

1(b)

Figure 1. Tapered transmission line matching section (a) ideal and (b) an approximation to the continuous taper used in modelling.

Theory for the tapered transmission line is readily available [3]. Relation between the characteristic impedance and the reflection coefficient (Γ) is given by:

$$\Gamma = \frac{1}{2}\int_0^L e^{-j2\beta z}\,\frac{d}{dz}\,(\ln\bar{Z})\,d \qquad (1)$$

Where L = total taper length and $\beta = 2\pi/\lambda$

By changing the type of taper profile one can obtain different passband characteristics. Two most commonly used and practical taper design line will be considered in this paper.

A. *Exponential Taper*

If the impedance profile varies exponentially when a function of the form ln Z is substituted in Equation 1 (i.e. $Z(z) = Z_C\, e^{az}$, where $a = \ln(Z_L/Z_C)/L)$, the reflection coefficient (Γ) can be derived [3] as shown below:

$$\Gamma = \frac{\ln(Z_L/Z_C)}{2}\, e^{-j\beta L}\, \frac{\sin\beta L}{\beta L} \qquad (2)$$

B. *Triangular Taper*

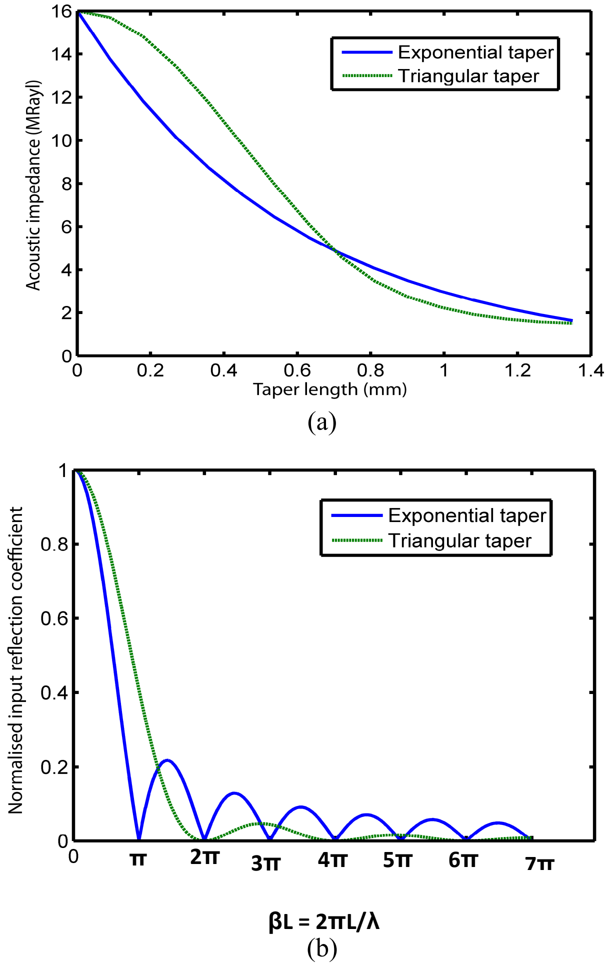
A matching section with a more desirable property could be achieved if a triangular function of the form shown below in Equation 3 is chosen. The impedance profile for this triangular taper and the overall reflection coefficient can be obtained from straightforward substitution of Equation 3 in Equation 1 and integrating it, and the result is shown below in Equations 4 and 5, respectively.

$$\frac{d(\ln\bar{Z})}{dz} = \begin{cases} \frac{4z}{L^2}\ln(\bar{Z}_L) & \text{for } 0 \le z \ge L/2 \\ \frac{4}{L^2}(L-z)\ln\bar{Z}_L & \text{for } L/2 \le z \ge L \end{cases} \qquad (3)$$

$$Z(z) = \begin{cases} Z_C\, e^{2\frac{z^2}{L}\ln\left(\frac{ZL}{ZC}\right)} & \text{for } 0 \le z \ge L/2 \\ Z_C e^{\left(\frac{4z}{L}-2\left(\frac{z}{L}\right)^2-1\right)\ln Z_L/Z_0} & \text{for } L/2 \le z \ge L \end{cases} \qquad (4)$$

$$\Gamma = \frac{1}{2}\ln\left(\frac{Z_L}{Z_C}\right) e^{-j\beta L}\left[\frac{\sin\beta L/2}{\beta L/2}\right]^2 \qquad (5)$$

A comparison of the synthesized impedance profile as a function of taper length and reflection coefficient as a function of βL for both the taper designs, is shown in Figure 2. For both the designs, the reflection coefficient is quiet small, approximately 22% for exponential taper and 5% for the triangular taper. However, the length of the triangular taper is almost twice that of an exponential taper.



(a)

(b)

Figure 2. Comparison of an exponential & triangular taper profile (a) synthesised impedance profile to match a composite transducer (16 MRayl) to a water load, and (b) the modelled normalised input reflection coefficients.

III. MANUFACTURE AND ASSEMBLY OF PASSIVE LAYERS

A. Manufacture of graded matching structure using photopolymerisation method

A range of photopolymerisable polymers have been investigated in order experimentally assess the tapered matching layer designs. Such an approach allows for a rapid realization of the tapers and eliminates additional bond-lines between the layers. Eliminating bond lines has been shown theoretically to improve device behavior in devices comprising multiple acoustic matching layer [4], it will also facilitate manufacture. A range of polymers, produced using a photocuring methodology have been investigated [7], the materials based on the glycidyl ether of bisphenol A (BisA) and 1,4-cyclohexanedimethanol diglycidyl ether (CHDG). The polymerization is initiated by the action of ultraviolet light on photoacid generator (PAG) that comprises triarylsulfonium hexafluorophosphate salt in 50% solution in propylene carbonate. When cured, Bis A produces a rigid material with a high glass transition temperature (T_g) whereas CHDG cures to a more flexible lower T_g material, by blending the two monomers a range of materials can be manufactured. Furthermore, the addition of particles to the uncured resin allows the acoustic impedance of the resultant polymer to be varied across a wider range. Therefore methodology facilitates the successive photocuring of thin layers of polymer, blends of polymer or particle loaded polymers in order to create the tapered profile required for the matching layer.

In order to manufacture the graded layers for the desired transducer design the following methodology was employed – 20g of monomer were mixed with 0.4g of PAG, using a Thinky planetary mixer (Intertronics, Oxon, UK). In order to reduce the viscosity during mixing and deposition, samples containing between 50 to 100% w/w BisA were heated to 60°C. In addition to blends of polymers, a range of materials based on the BisA resin and incorporating barium sulphate ($BaSO_4$) particles were also prepared. Incorporation of $BaSO_4$ inot the polymer will result in increase acoustic impedance. Specimens were produced containing 12, 18, 26, 35 and 51g of $BaSO_4$ with 20g of BisA with 0.4 g of PAG to obtain 13, 19, 25, 31 and 40% volume fractions of $BaSO_4$, respectively.

The range of specific acoustic impedances that can be achieved using the blends of BisA and CHDG is illustrated in Figure 3. These data were determined by through transmission time-of-flight measurements at 500kHz and an Anton Paar Digital DMA601 density-measuring cell and a DMA60 density meter (Stanton Redcroft, London). The CHDG material is more flexible at room temperature and this in reflected in the lower value of specific acoustic impedance for this material. Increasing the amount of BisA in the formulation, results in an increase in the specific acoustic impedance of the resultant polymer. The density variation is minimal across the range of materials and the increase in the acoustic impedance reflects the increased acoustic velocity, and concomitant increase in moduli of the material as the percentage of BisA in increased. Figure 4 details the variation of the specific acoustic impedance, determined at as before, for the range of samples containing $BaSO_4$, an almost linear variation with respect to volume fraction is observed.

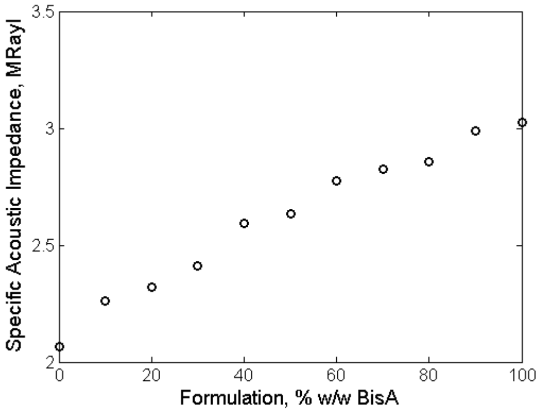


Figure 3. Variation in specific acoustic impedance of the matching layer, as the percentage of BisA is varied

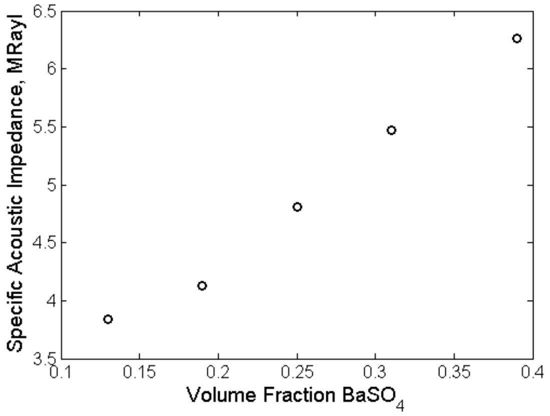


Figure 4. Variation in specific acoustic impedance as the volume fraction of $BaSO_4$ in BisA is varied

In order to manufacture the films in thin film format to manufacture the graded matching layer structure a K-Bar deposition system (RK Print and Coat, Herts, UK) was used. The general procedure was as follows, a 1ml aliquot of the monomer was deposited onto a Teflon plate, and the K-Bar system was used to produce a wet film thickness of 100μm, the wet film was exposed to UV light using an IUV 250 flood lamp (Intertronics, Oxon, UK) for 3 minutes, giving a dose of 5000mJ/cm2. This resulted in a ~90μm cured film. The monomer to form the next layer of the matching layer gradient was then deposited on top of the cured layer and the process repeated till all of the layers had been deposited and cured. An overall taper length of 0.76mm thick (approx. λ/2 in water), with an exponential gradient profile is considered for the initial investigation. The salient properties of a graded matching profile manufactured using the photopolymerisation technique is presented in Table 1.

B. Transducer fabrication

The fabricated graded matching layer is bonded onto a conventional thickness mode composite device, made of 50% volume fraction (PZT-5A) and hard-set polymer (CY1300/1301), with a nominal operating frequency of 1MHz. A 6MRayl non-conducting backing based on tungsten loaded epoxy was attached to the active layer prior to marinising the device.

Layer #	1	2	3	4	5	6	7	8
Modelled Z (MRayl)	6.26	5.44	4.73	4.12	3.57	3.1	2.7	2.34
Measured Z (MRayl)	6.26	5.47	4.69	4.13	3.57	3.02	2.7	2.32
Material	39%	31%	25%	19%	5%	0%	45%	80%
	Volume fraction $BaSO_4$					**% BisA**		
Velocity Long (m/s)	2519	2473	2417	2257	2369	2568	2297	2003
Velocity Shear (m/s)	1281	1208	1169	1156	1152	1093	932.5	799.5
P (kg/m3)	2487	2214	1991	1829	1324	1178	1175	1159

Table 1. Manufactured matching layer materials properties for an exponential taper design

IV. EXPERIMENTAL RESULTS

Device operational impedance characteristic of the prototype device was measured coupled to a water load using a HP impedance/gain-phase analyser (Agilent, South Queensferry, UK), the result is shown in Figure 5. It is clear that the device operates around a centre frequency around 1MHz. Also the electrical impedance change within the operational bandwidth is reasonably smooth. Consequently the device ring-down time will be shorter - resulting in a wider bandwidth. Attaching such graded matching layers at the front face of the transducer also enhances the sensitivity of the device, as it efficiently propagates energy into the load medium. Pulse-echo measurement was performed in water with a planar Crown glass block used as the reflector. The device was connected via BNC cable to a JSR PR35 Pulser/Receiver (JSR Ultrasonics, Pitttsford, NY) and the signal recorded using an Infiniium 54832D digitizing oscilloscope (Agilent, South Queensferry, UK.). The time, and Fourier transformed frequency domain, impulse response of the device is shown in Figure 6. The device exhibits approximately 80% fractional bandwidth.

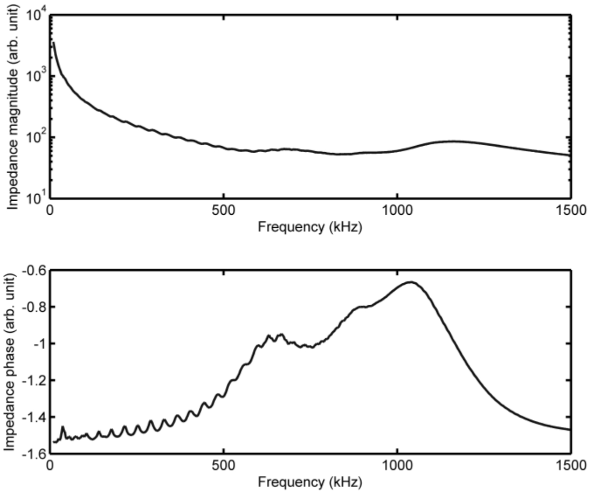


Figure 5. Active layer operational impedance profile measured using an impedance analyser

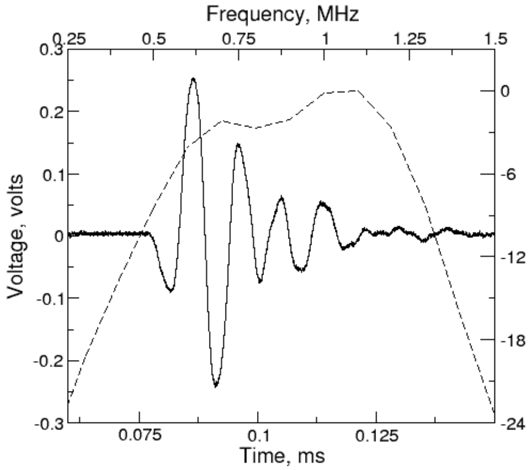


Figure 6. Time and frequency domain pulse echo impulse response result of the 1 MHz thickness mode transducer with graded matching layers radiating into a water load, and 6MRayl backing

V. CONCLUDING REMARKS

A preliminary investigation into the use of tapered transmission line filter techniques to design matching layers for piezoelectric transducers. In order to achieved the desired layer structure a photopolymerisation polymer has been employed. The experimental and simulation results that have been presented demonstrate the feasibility of the technique in. In the current context an exponential equal taper, with consistent layer thickness and acoustic impedance taper is considered. However, it is expected that difference taper profile and optimized the layer parameters will results in improved behavior of this type of device. This will be the subject of future work.

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