OPTIMISATION METHOD FOR ULTRASONIC TRANSDUCERS USED IN MEDICAL IMAGING

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ABSTRACT

An optimisation method for ultrasonic transducers used in medical imaging applications is presented. This method is based on the minimisation performance index using the simplex method and only requires the calculation of the transducer impulse response. This optimisation is performed on a transducer made of one piezoelectric layer and from one to four quarter-wavelength matching layers. From these results, a transducer with two matching layers is fabricated and characterised. Our optimisation method allows to monitor the manufacture of a transducer by correcting, step by step, drifts observed at the different stages of transducer fabrication.

INTRODUCTION

Optimisation approaches for ultrasonic transducers are often limited to one configuration and depend on the application. Several analytical approaches have been developed. Desilets [1] theory gives acoustic impedances of the quarter wavelength matching layers according to their number. However, this method is limited to the case of an air backing transducer. Besides, the transducer geometry is not taken into account. Later, McKeighen [2] extended this theory taking into account acoustic impedance of the backing.

In addition to these analytical approaches, methods based on the minimisation index have been developed [3] [4]. The choice and the weighting of parameters which define the transducer quality (sensitivity, resolution, bandwidth) depend on the chosen application. These parameters are usually calculated from the impulse response and are gathered in a performance index. Transducer optimisation consists in the minimisation of this index and from the minimum value, electromechanical and geometrical properties of the different transducer elements can be deduced.

In this paper, an optimisation method based on an index and parameters introduced by Thijssen [4] is presented. It is independent of transducer configuration and allows the optimisation of complex transducers. Indeed, it only requires the impulse response to be calculated. Therefore, this method can have a large field of applications.

In the first section, our method is presented and in particular, the definition of our performance index for medical imaging and the differences between Thijssen index and our own. Then, this optimisation is applied to a transducer made with a ferroelectric ceramic, a backing and several matching layers, and results are discussed. Finally, in the third section, a transducer is fabricated from an optimised two matching layers configuration and characterised. Experimental characteristics are compared with optimisation results.

ULTRASONIC TRANSDUCER OPTIMISATION

The method is based on the minimisation of a performance index. The main difficulty is first to choose the parameters which compose this index. These parameters are determined as a function of the application. For medical imaging, the transducer must have good resolution while keeping high sensitivity and the best trade-off must be found between these two conditions. In order to quantify these properties, the 20 dB duration of impulse response and the insertion loss can be used. Thijssen [4] defined new parameters to limit discontinuity risks during iterations of minimisation. These parameters (called here d_{20}, d_{40} and RTEF) are calculated from impulse response envelope. In each optimisation iteration, the impulse response is calculated with KLM model [5] [8] and the three parameters are deduced. The value of d_{20} (resp. d_{40}) is defined as the smallest length corresponding to 96.8% (resp. 99.76%) of the area of impulse response envelope. Noting TF the emission-reception transfer function of transducer, RTEF is an energy term defined by :

$$RTEF = -10 \log_{10}\left(\int_0^{\infty} \left| TF(f) \right|^2 df \right).$$

The second difficulty to elaborate the performance index is the choice of the weighting parameters noted (α,β,γ) applied respectively to (d_{20}, d_{40}, RTEF). They allow to take into account the importance of one parameter relative to the others. For medical imaging, Thijssen used an empirical weighting (3,2,1) and we tried several weighting combinations to confirm that they give consistent results in accordance with experimented designers.

In our minimisation method, d_{20} and d_{40} are used because, in addition to describe correctly the axial resolution, these parameters allow to avoid discontinuities. On the other hand, the sensitivity will be quantified by the amplitude of the impulse response envelope maximum. Indeed, this term, versus RTEF, is independent of bandwidth and then independent of d_{20} and d_{40}. This amplitude term is noted amp and expressed in s^{-1}. The performance index, noted x, is defined by :

$$x = \alpha.10.\log_{10}(d_{20}) + \beta.10.\log_{10}(d_{40}) - \gamma.10.\log_{10}(amp).$$

From an initial configuration of the transducer, using the KLM scheme [8], the impulse response and consequently the performance index are first calculated. Using a simplex minimisation [6], transducer characteristics (for example thickness and acoustic impedance of matching layers) are modified by iteration to obtain the minimal index. In order to avoid discontinuities and to reduce the convergence duration, initial values have to be chosen not too far from the optimum ones. That’s why values halfway between Desilets’ [1] and Mc Keighen’s ones [2] are used.

OPTIMISATION OF A TRANSDUCER MADE OF SEVERAL MATCHING LAYERS

Several configurations with one to four matching layers are considered in 50Ω environment for a ferroelectric lead titanate ceramic disc (Pz34 [7]). Characteristics of this ceramic are obtained by the measurement of the electrical impedance and are given in Table 1. These parameters will be introduced in KLM model to simulate the electro-acoustic behaviour of a transducer including this ceramic disc.

The optimisation is performed for several fixed values of backing acoustic impedance (Z_B in MRa) where this backing is considered as a semi-infinite medium. Results are shown as variations of performance index x (dB), d_{20} and d_{40} durations (periods), amp (s^{-1}), quarter-wavelength layer thickness (y_{layer} in $\lambda/4$) and acoustic impedance (Z_{layer} in MRa), active layer thickness (y_{piezo} in $\lambda/2$) and series inductance (induc in µH), all as a function of Z_B.

Table 1 : Characteristics of Pz34 ceramic (resonance frequency is noted f_a; k_t: thickness coupling factor; δ_m: mechanical losses; δ_e: dielectric losses; e^S_{33r} : relative dielectric constant at constant strain; Z: acoustical impedance)

velocity(m/s)	k_t (%)	δ_m (%)	δ_e (%)	e^S_{33r} at f_a	Z (MRa)
4800	40.1	0.4	2	174	36.3

During the optimisation, the modified transducer characteristics are thickness (y_{layer}) and impedance (Z_{layer}) of each matching layer and an inductance (induc) connected in series for electrical matching. Moreover, a centroid frequency is imposed. This frequency noted f_{ce} is defined from the transfer function in emission – reception (noted TF) such as :

$$f_{ce} = \left(\int_0^\infty |TF(f)| f df\right) \Big/ \left(\int_0^\infty |TF(f)| df\right).$$

In order to keep f_{ce} constant at each iteration of our optimisation, the thickness of piezoelectric ceramic (y_{piezo}) will be allowed to change during the minimisation of x.

The one matching layer configuration is studied first. The results are shown in Figure 1. A very low variation of x is observed as a function of Z_b. This means that many configurations can be retained and those corresponding to technological facilities will be judicious. The mean value of performance index (in the range of Z_b calculated) is around –281 dB, which corresponds to a d_{20} value about 4.5 periods, a d_{40} value about 8 periods and an amplitude value about 0.48 s^{-1}. The backing acoustic impedance will be chosen according to the sensitivity – bandwidth compromise necessary for the desired application. If the sensitivity is the most important parameter, a low backing impedance will be chosen. On the contrary, if the impulse response must be the shortest possible, the backing impedance will have to be increased. The matching layer impedance is around 4 MRa, that is to say a value halfway between Desilets' [1] and Mc Keighen's ones [2]. The matching layer has a quarter wavelength thickness.

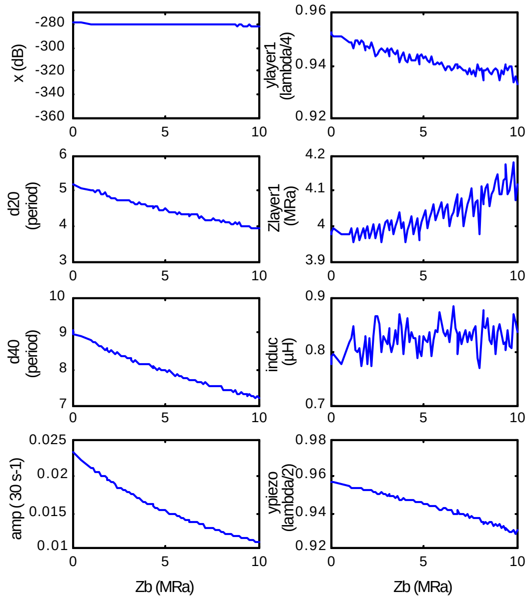

Figure 1 : Optimisation results for a transducer made of a Pz34 ceramic disc and one matching layer.

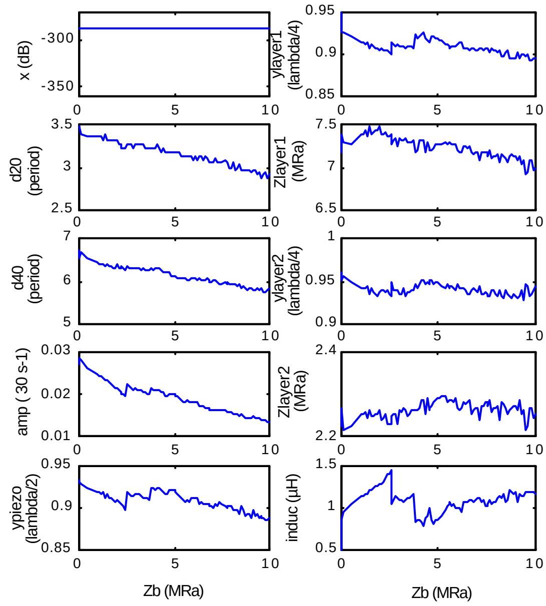

Figure 2 : Optimisation results for a transducer made of a Pz34 ceramic disc and two matching layers.

The second optimisation takes into account two matching layers (Figure 2). The mean value of x is around –288 dB, that is to say a d_{20} value about 3 periods, a d_{40} value about 6 periods and an amplitude value about 0.6 s^{-1}. The matching layers have almost quarter wavelength thicknesses.

Three matching layers and four matching layers configurations have also been optimised. The results are summarised in Table 2. If we compare the first two configurations, we note that the performance gain is around 7 dB, that is to say a d_{20} gain about 35%, a d_{40} gain about 25% and a amplitude gain about 25%. The gain obtained with a second matching layer justifies the setting up of more complex manufacturing technology and consequently more expensive manufacturing cost.

Table 2 : Comparison of performances for configurations including from one to four matching layers

	One matching layer	Two matching layers	Three matching layers	Four matching layers
x (dB)	-281	-288	-290	-291
d_{20} (period)	4.5	3	2.8	2.6
d_{40} (period)	8	6	6	6
amp (s^{-1})	0.48	0.6	0.6	0.6

However, for two matching layers and three matching layers configurations, x values are very close (2 dB gain). Variations of d_{20}, d_{40} and amp are very small (6% for d_{20}). Optimisation results are similar and a kind of saturation phenomenon is observed. Impulse responses obtained with the four configurations are shown in Figure 3. We can easily observe that the performance gain between the two last configurations is very small.

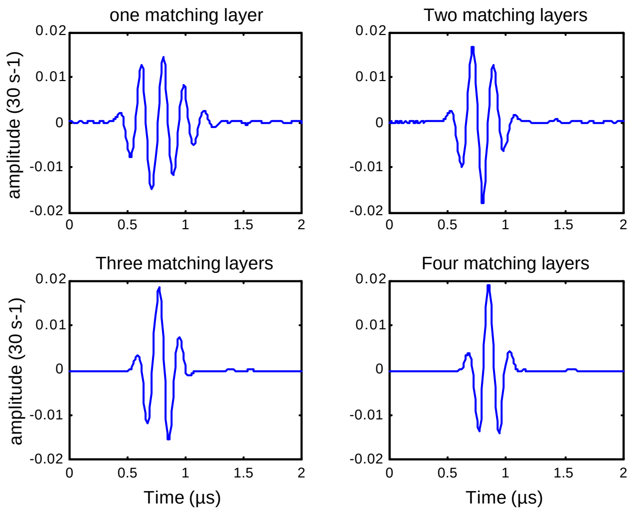

Figure 3 : impulse responses of a transducer made of a Pz34 ceramic disc and from one to four matching layers.

ELABORATION OF AN OPTIMISED TWO MATCHING LAYERS TRANSDUCER

The piezoelectric material used for the transducer is a lead titanate ceramic whose characteristics are shown in Table 1. The ceramic diameter is 19.3 mm and the ceramic thickness is 453 µm corresponding to a resonance frequency around 5 MHz. The reference optimisation is shown in Figure 2. The chosen backing acoustic impedance is 5 MRa. This value is taken from Figure 2 and the optimum thicknesses and acoustic impedances of matching layers are deduced (Table 3).

Table 3 : performances and characteristics for a 5 MRa backing.

Performances		Characteristics	
x = -288 dB	amp = 0.6 s^{-1}	$y_{piezo} = 0.91\ \lambda/2$	induc = 0.9 µH
d_{20} = 0.6 µs	d_{40} = 1.2 µs	$y_{layer1} = 0.92\ \lambda/4$	$y_{layer2} = 0.95\ \lambda/4$
or d_{20} = 3.2 periods	or d_{40} = 6 periods	Z_{layer1} = 7.3 MRa	Z_{layer2} = 2.3 MRa

Three passive materials have been elaborated. Their respective acoustic impedances are 5 MRa (backing), 7.3 MRa (first matching layer) and 2.3 MRa (second matching layer). However, characteristics (velocity, acoustic impedance, attenuation…) used in the optimisation and measured on these materials are not exactly the same. In order to take into account the differences, a new optimisation is performed where the measured acoustic properties are considered as fixed values.

Besides, during the transducer fabrication, we noticed differences between theoretical and experimental values, particularly in term of impedance and thickness (for example 6 µm difference for the first layer thickness). To avoid too important shifts of transducer performances, at each manufacturing step, thickness and acoustic impedance of the previous layers are measured and reintroduced in the optimisation. So the optimisation allows to control the whole elaboration of a transducer while keeping best performances. The final optimisation is summarised in Table 4.

Table 4 : Optimum performances and characteristics of the fabricated transducer (with a 5 MRa backing).

Performances		Characteristics	
x = -281 dB	amp = 0.45 s^{-1}	y_{piezo} = 453µm	induc = 1 µH
d_{20} = 0.66 µs	d_{40} = 1.9 µs	y_{layer1} = 86 µm	y_{layer2} = 127µm
or d_{20} = 3.5 periods	or d_{40} = 9 periods	Z_{layer1} = 7.3 MRa	Z_{layer2} = 2.3 MRa

In order to characterise the transducer, electrical impedance is measured. For this, we use a Hewlett Packard spectrum analyser (HP 4195A) with an impedance test kit. Real and imaginary parts of impedance versus frequency are acquired in air (impedance : Z_m = 400 Ra) and in water (impedance : Z_m = 1.5 MRa). Theoretical and experimental results are in a good agreement. Resonance frequencies are identical. Due to the inductor, real part of impedance is equal to zero at resonance frequency.

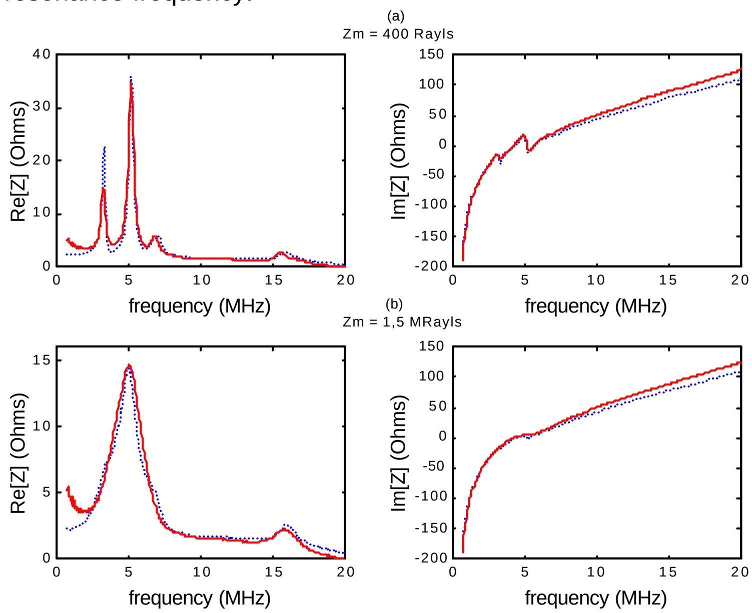

Figure 4 : theoretical (solid line) and experimental (points) real and imaginary parts of transducer impedance in air (Z_m=400Ra) and in water (Z_m=1.5 MRa).

Furthermore, the transfer function in transmit-receive mode is measured by reflection on a steel target. The transducer theoretical behaviour has been simulated once again taking into account the electrical impedance of the generator (Z_{gene}=23Ω) and a coaxial cable which has a length of 1 meter. Experimental (points) and theoretical (solid lines) impulse responses are shown in Figure 5(a). Results are in a good agreement, particularly before one microsecond. Experimental d_{20} and d_{40} values are respectively 0.9 µs and 2µs. If d_{40} value is close to the expected one, d_{20} is influenced by perturbations at the end of impulse response. The normalised frequency responses are shown in Figure 5(b). Results are in a good agreement too. The maximum frequency is 5.1 MHz in theory and 4.8 MHz in practice, that is to say a 5% gap. Centroï d frequencies are very close (4.65 MHz in theory against 4.7 MHz in practise). There is a good agreement between theoretical and experimental bandwidth which are respectively around 53 % and 56%.

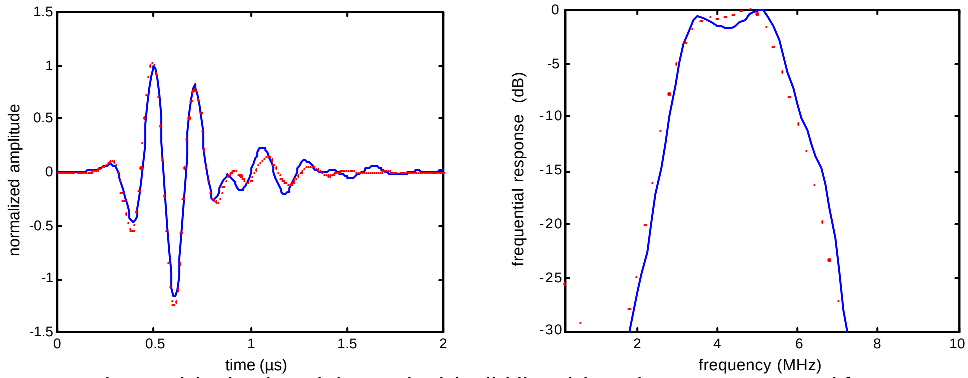

Figure 5 : experimental (points) and theoretical (solid lines) impulse responses and frequenty responses of fabricated transducer. The coaxial cable is taken into account and the pulser output impedance is Z_{gene}=23Ω.

As this method is independent of transducer configuration, the combination of multilayer K.L.M. scheme [8] and this optimisation method allows the feasibility study of a two-active-layer transducer for harmonic imaging (which can have a dual-frequency behaviour) [9].

CONCLUSION

An optimisation method for ultrasound transducers based on the minimisation (by simplex method) of a performance index is presented. Results give the optimal configuration of the studied transducer. From the minimal value of performance index (x), optimum acoustic impedance of backing and physical characteristics of the transducer (thickness and impedance of matching layer, thickness of active layer, series inductance) are deduced. A saturation of performance gain is observed with increase of matching layer number. Finally, a two matching layers transducer is fabricated from optimisation results. We show that our method can be used to correct step by step manufacturing shifts (faulty thicknesses or different acoustic properties). Electrical impedance, frequency and impulse responses are measured and compared with theoretical ones: a good agreement between theory and experiments is observed.

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