Ultrasonics xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Modelling of a novel high-impedance matching layer for high frequency (>30 MHz) ultrasonic transducers

Y. Qian, N.R. Harris *

School of Electronics and Computer Science, University of Southampton, University Road, SO17 1BJ Southampton, UK

ARTICLE INFO

Article history:
Received 7 May 2013
Received in revised form 19 August 2013
Accepted 19 August 2013
Available online xxxx

Keywords:
Transducer
Matching
Simulation
Modelling
High-frequency

ABSTRACT

This work describes a new approach to impedance matching for ultrasonic transducers. A single matching layer with high acoustic impedance of 16 MRayls is demonstrated to show a bandwidth of around 70%, compared with conventional single matching layer designs of around 50%. Although as a consequence of this improvement in bandwidth, there is a loss in sensitivity, this is found to be similar to an equivalent double matching layer design. Designs are calculated by using the KLM model and are then verified by FEA simulation, with very good agreement Considering the fabrication difficulties encountered in creating a high-frequency double matched design due to the requirement for materials with specific acoustic impedances, the need to accurately control the thickness of layers, and the relatively narrow bandwidths available for conventional single matched designs, the new approach shows advantages in that alternative (and perhaps more practical) materials become available, and offers a bandwidth close to that of a double layer design with the simplicity of a single layer design. The disadvantage is a trade-off in sensitivity. A typical example of a piezoceramic transducer matched to water can give a 70% fractional bandwidth (comparable to an ideal double matched design of 72%) with a 3 dB penalty in insertion loss.

1. Introduction

Piezoelectric ceramics have been used in many broadband transducers in the field of ultrasonics for several decades [1]. The ultrasonic waves generated by the ceramic layer radiate into a low-impedance fluid load (usually water). However, the impedance mismatch between the ceramic and the water medium causes low energy transfer efficiency and a narrow bandwidth. However, it is well known that this efficiency can be improved by inserting single or multiple matching layers to cancel the energy reflection at the interface of the two mediums [2].

For piezoelectric ceramic transducers driving into water, a bandwidth of 40–50% can be achieved by using conventional single matching layers. Up to 70% can be achieved by using double matching layers, while applying more matching can in principle further increase the bandwidth [2]. Nevertheless, multiple matching layers are not widely used in current transducers, especially for high frequency (>30 MHz) applications, mainly because of fabrication difficulties. These include layer adhesion, thickness accuracy, and selection of applicable materials. With increasing frequency, these issues become more significant, as dimensional tolerances become finer. Although much effort has been expended on the alternative approach of modifying the acoustic impedance of piezoelectric materials to increase the bandwidth, for example, by using piezoelectric composites or polymers [3,4], there are few publications that address the problem of matching layer design. This is because the standard methods for impedance matching are well defined. However, in this paper, the use of higher impedance materials for single layer matching systems is explored, rather than the traditional method of using impedances between those of the two layers to be matched. Traditionally, impedances lower than 10 MRayls would be used in order to match piezoceramics and water, in itself causing issues for material selection. Here, however, we model the use of higher impedances of around 16 MRayls with success, allowing more accessible materials to be used, such as certain types of glass. Such an approach offers an improved bandwidth (comparable to double layer matching), with an acceptable loss in sensitivity, offering a good compromise between bandwidth, ease of construction and insertion loss.

This paper is organised in the following way: In Section 2 we briefly discuss a typical transducer construction and describe the principle of matching and the use of quarter-wave sections. The paper then describes an alternative approach utilising a combination of electrical and mechanical matching that allows an extension of the transducer bandwidth. Section 3 illustrates the approach by investigating the design of a 30 MHz PZT based transducer with a single matching layer using classical 1D KLM modelling in order to illustrate the mechanisms at work. This is then verified by FEA analysis, and the comparison of the results discussed, with concluding remarks in Section 4.

* Corresponding author. Tel.: +44 2380593274.
E-mail address: nrh@ecs.soton.ac.uk (N.R. Harris).

0041-624X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultras.2013.08.012

2. Design of high-impedance single matching layer

Fig. 1 illustrates the cross-section of a typical transducer structure, including backing layer, ceramic layer and matching layer(s). The transducer is designed to facilitate the transmission of ultrasound from the ceramic piezoelectric material to the fluid medium (typically water). In principle, the transducer can be made by several different techniques, such as thin-film, machined ceramic, or dice and fill composites, For the purposes of this paper we assume the transducer is a piezoceramic layer, but the matching techniques described are not constrained by this assumption.

In the example shown, the backing layer itself is terminated at an air boundary, and the fluid layer is considered infinite.

Since the acoustic impedance of a commonly-used ceramics is around 35 MRayls, and the value for water is only 1.5 MRayls, this impedance mismatch causes inefficient ultrasonic transmission as in effect the ultrasonic energy cannot escape from the piezoelectric material. To increase the efficiency, matching layer(s) with characteristic thicknesses of $\lambda_m/4$ (λ_m – wavelength of sound in the matching layer at the transducer resonance) are introduced between the piezoelectric ceramic and the fluid medium, whose acoustic impedance follows a conventional design rule expressed below [2],

$$Z_m = \sqrt{Z_0 Z_R} \tag{1}$$

where Z_m, Z_0, Z_R are the acoustic impedances of the matching material, ceramic and fluid load (or water), respectively. Thus the impedance of a single ideal matching layer is about 7 MRayls. There are very few useful materials with acoustic impedance near this value, and so compromises have to be made. Epoxies commonly used to form a matching layer have their acoustic impedance in the range of 2–4 MRayls and are sometimes used in transducers. They give some useful improvement in bandwidth compared with having no matching layer, but at a cost in terms of sensitivity compared with an ideal match. To reach the impedance of 7 MRayls for ideal matching, heavy particles must be loaded into the epoxy to increase its impedance [5].

However, the ideal matching layer only realises the maximum energy transfer from the ceramic front surface to the fluid medium at the resonance of the ceramic; the energy efficiency reduces as the operating frequency moves away from the resonance. This is now discussed in more detail, with a view to explaining how it is possible to improve the bandwidth of single layer designs, and we start by looking into the matching principle. Fig. 2 shows an equivalent circuit of the transducer where the quarter-wavelength matching layer can be treated as a transmission line and is represented by a transfer matrix ABCD. Here the transducer without matching layer is treated as a black box, and Z_{in} is the input impedance to represent the matching layer and fluid load combined, as seen by the transducer.

For a transducer without matching layer, the impedance mismatch is the difference between Z_0 and Z_R; while for the one with

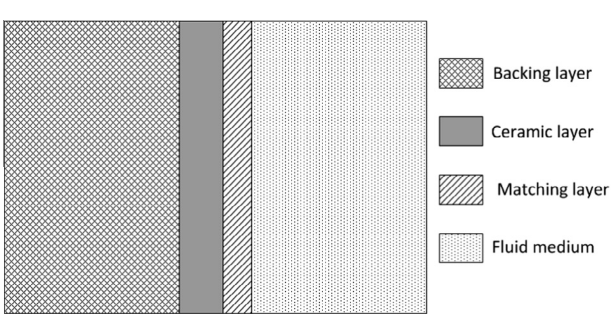

Fig. 1. Cross-section of a typical transducer.

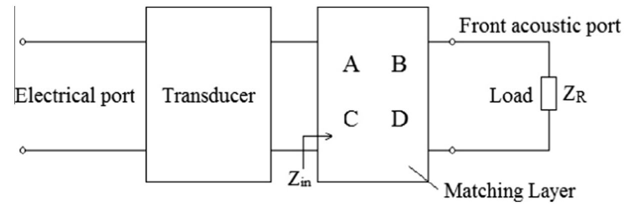

Fig. 2. Equivalent circuit of a transducer with matching layer represented by transfer matrix.

matching layer, it actually becomes the difference between Z_0 and Z_{in}. If $Z_{in} = Z_0$, the mismatch will be eliminated and therefore no mechanical energy loss will be found in the interface during the transmission, and so it is important to investigate the behaviour of Z_{in} as the driving frequency moves away from the resonant frequency. The equation describing Z_{in} is expressed as follows [6],

$$Z_{in} = \frac{AZ_R + B}{CZ_R + D} \tag{2}$$

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix} = \begin{vmatrix} \cos(kd) & jZ_m \sin(kd) \\ j\sin(kd)/Z_m & \cos(kd) \end{vmatrix} \tag{3}$$

where k is the wave number ($k = 2\pi/\lambda$, λ – wavelength), and d denotes the thickness ($d = \lambda_0/4$). Thus the amplitude of Z_{in} is expressed as,

$$|Z_{in}| = \left|\frac{Z_R\cos(kd) + jZ_m\sin(kd)}{\cos(kd) + j\sin(kd)Z_m/Z_r}\right| = Z_m \cdot \sqrt{\frac{Z_R^2\cot^2(kd) + Z_m^2}{Z_m^2\cot^2(kd) + Z_R^2}} \tag{4}$$

By using the definitions of $k = 2\pi/\lambda$ and $d = \lambda_0/4$, Eq. (4) can be further simplified to,

$$|Z_{in}| = Z_m \cdot \sqrt{\frac{Z_R^2\cot^2(\theta) + Z_m^2}{Z_m^2\cot^2(\theta) + Z_R^2}}; \tag{5}$$

$$\theta = \frac{\pi}{2}\cdot\frac{\lambda_0}{\lambda} = \frac{\pi}{2}\cdot\frac{f}{f_0} \tag{6}$$

where f and f_0 refers to the driving frequency and resonant frequency, respectively. Here θ is an author-defined parameter related to the transducer bandwidth. The −6 dB fractional bandwidth is determined by the lower and higher cut-off frequency f_H, f_L respectively, with their relations expressed as follows:

$$BW = (f_H - f_L)/f_c; \quad f_c = (f_L + f_H)/2 \tag{7}$$

where BW denotes the −6 dB fractional bandwidth, f_C is central frequency and is generally equal to transducer resonant frequency f_0. By using Eqs. (6) and (7) and assuming that $f_C = f_0$, it is found that,

$$BW = \frac{2}{\pi}(\theta_H - \theta_L); \quad \theta_0 = \frac{\pi}{2} \tag{8}$$

where θ_0, θ_L and θ_H are the θ values at f_0, f_L and f_H respectively. Assuming that the fractional bandwidth has a maximum of 1, this gives a range of values for θ ranging from

$$\theta_L = \theta_o - \frac{\theta_o}{2} = \frac{\pi}{2} - \frac{\pi}{4}; \quad \theta_H = \theta_o + \frac{\theta_o}{2} = \frac{\pi}{2} + \frac{\pi}{4} \tag{9}$$

Consequently, the range of the factor "$\cot^2(\theta)$" in Eq. (5) is obtained, which varies from 0 for a BW of zero, to 1 for a BW of 1. Since Z_m in most transducer applications is much larger than Z_R, it is reasonable to assume that $Z_m^2 \gg Z_R^2$. Thus the assumption of $Z_m^2 \gg Z_R^2\cot^2(\theta)$ becomes valid as well. Eq. (5) can be simplified to,

$$|Z_{in}| = Z_m^2 \cdot \sqrt{\frac{1}{Z_m^2\cot^2(\theta) + Z_R^2}} \tag{10}$$

Please cite this article in press as: Y. Qian, N.R. Harris, Modelling of a novel high-impedance matching layer for high frequency (>30 MHz) ultrasonic transducers, Ultrasonics (2013), http://dx.doi.org/10.1016/j.ultras.2013.08.012