THERMAL EFFECTS IN PIEZOELECRIC TRANSDUCERS THEORETICAL AND EXPERIMENTAL RESULTS

V.Loyau, G. Feuillard, L.P. Tran Huu Hue.
LUSSI-GIP Ultrasons, FRE CNRS 2448, rue de la chocolaterie 41034 Blois Cedex France.
Loyau@univ-tours.fr

Abstract
In this paper, a new formulation of the electrical input impedance of a single element transducer is presented. The resistive part of the electrical impedance that takes into account losses in each component of the transducer is split into a radiation term on one hand and into dissipation terms on the other hand. Based on energy conservation, the temperature increase in a transducer can be calculated. Furthermore, coupled with thermal equations, one can calculate the temperature increase in steady state. These theoretical results are confirmed by temperature measurements on a single-element transducer.

Introduction
To date little attention has been paid to the study of thermal dissipation in ultrasonic transducers [1]. Nevertheless, for several applications such as therapy or Doppler imaging, the temperature rise in the probe can lead to a degradation of its performance and a discomfort for the patient, and even slight to burns.
The objective of this work is to develop a model that can predict the temperature rise of an ultrasonic transducer in steady state. We have used the one dimensional Mason model to calculate the equivalent dissipation resistances in each part of the transducer (piezoceramic, backing, and matching layers). Knowing the thermal characteristics (heat capacity and thermal conductivity) of the constitutive elements, we have calculated the profile of the thermal sources in the transducer. We then have coupled the result with a thermal diffusion numerical model in order to calculate the temperature rise in a single-element transducer in steady state.
Temperature measurements in transient regime, (where it is assumed that there are no heat exchange), and in steady state were carried out on a single element transducer in order to validate the theoretical results. In transient regime, dissipation resistance is then deduced.

Theory
Let us consider the electro-acoustic Mason [2] model for a piezoelectric plate where dielectric losses, δ_e, and mechanical losses, δ_m, are taken into account (Figure 1). This means that the wave vector, k, the acoustical impedance of the piezoelectric medium, Z_p, and the static capacitance, C_o, are now complex. Introducing the global loss term, δ [3], $\delta = (1-k_t^2).\delta_m + k_t^2.\delta_e$ these parameters become:

k'= k.(1-i.δ/2)

Zp'= Zp.(1+i.δ/2)

Zco'= Zco.(1+iδ_e) = 1/(iCo.ω) +R where R is a resistance and ω is the pulsation

Each term or the Mason equivalent circuit (electrical or mechanical) can then be separated into a real and imaginary term:

Z_1 = Re [-i.Z_p'.tan(k'd/2)]

Z_2 = Im [-i.Z_p'.tan(k'd/2)]

Z_3 = Re [i.Z_p'/sin(k'd)]

Z_4 = Im [i.Z_p'/sin(k'd)]

where d is the thickness of the piezoceramic.

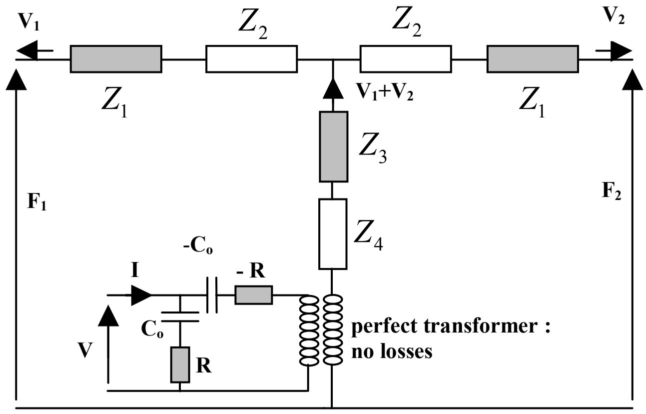

Figure 1: Mason's model with losses

The electrical input impedance, Z(ω), of the ceramic is complex and its real part allows to calculate the global power, P(ω), consumed by the ceramic:

$$<P>= ½ Re(Z(ω))I I^* \qquad (1)$$

When a transducer with a backing and two matching layers is considered (figure2), the global power consumed by the transducer can still be calculated. However, it is not possible to separate the power consumed by each component of the transducer from the power radiated into the propagating medium.
Here, we have developed an analytical calculation in which the contribution of each component of the transducer to the real part of the electrical input impedance can be separated. For a transducer with a backing and two matching layers, the real part of the impedance is split up in five equivalent resistances (figure 3).
R_a represents the energy dissipation in the propagating medium (water) by creation of an ultrasonic wave. $R_{loss-piezo}$, $R_{loss-back}$, $R_{loss-match1}$ and $R_{loss-match2}$ are respectively dissipation terms in the backing the piezoelectric ceramic and the two matching layers.

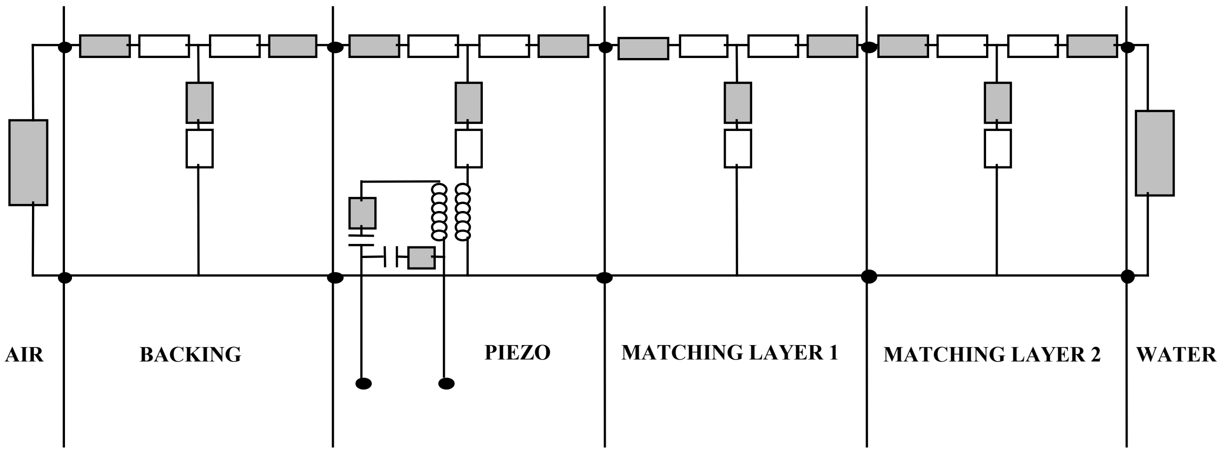

Figure 2: scheme of a complete transducer including losses (grey dipoles: real terms).

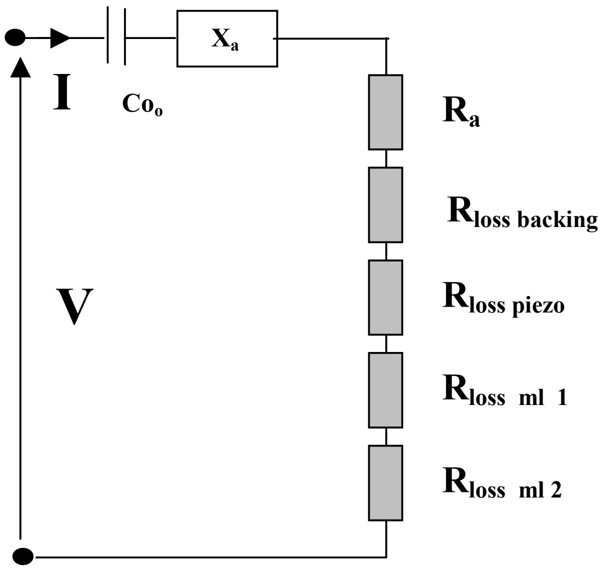

Figure 3: equivalent diagram for the electrical port

The power consumed by these resistances will be converted into heat and they will be at the origin of the temperature increase in the transducer.
Based on these considerations, simulations were carried out on a 10 MHz single element transducer the main characteristics of which are given in table 1. It is a transducer based on a hard PZT with a light backing and two matching layers dedicated to medical applications. Figure 4 shows the equivalent loss resistance of each component of the transducer.

Table 1: Transducer configuration

Backing	Z = 4 MRayl thickness = 10 mm attenuation = 0.3db/mm/MHz
Piezo ceramic	Ferroperm PZ 26 fo = 10 MHz losses : $\delta_m = 1$ % , $\delta_e = 1$ %
Matching layer 1	Z = 7.1 MRayl thickness = $\lambda/4$ attenuation = 0.1 dB/mm/MHz
Matching layer 2	Z = 2.2 MRayl thickness = $\lambda/4$ attenuation = 0.1 dB/mm/MHz
Propagating medium	Water : Z = 1.5 MRayl

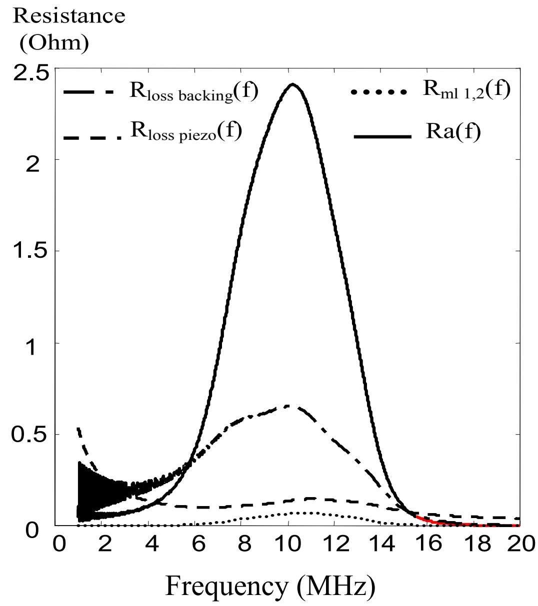

Figure 4 : plots of the equivalent loss resistances

Each loss resistance expression depends not only on loss term of the element it's related to, but also on loss terms of other components. Here, the radiation resistance dominates which means that the transducer is efficient. Most of the lost energy is converted into heat in the backing. Knowing the heat capacity of each transducer component, it is possible to calculate the temperature increase of the component as function of time. In the piezoceramic, the temperature increase, ΔT, is given by:

$$\Delta T = \frac{\langle P_{piezo} \rangle}{C_p} \Delta t \qquad (2)$$

with $\langle P_{piezo} \rangle = \frac{1}{2} R_{loss\ piezo} \langle I.I^* \rangle$

where $\langle P_{piezo} \rangle$ is the average power consumed by the ceramic, I is the current, Cp, the heat capacity and Δt is the time duration.

Experiments

In order to confirm these theoretical results, experiments were carried out on a 1.15 MHz single element transducer. It consists in a soft PZT ceramic with high losses (Navy type II) glued on a light epoxy backing. Figure 5 shows the experimental set up. The transducer is placed into a temperature-controlled cabinet and is loaded by air. A harmonic function generator (HP 3414 A) coupled with a power amplifier (ENI 150 A) delivers a quasi-continuous sinusoidal wave to the transducer. For a given frequency, the temperature is measured with a platinum probe (PT 100) on the edge of the transducer (either on the ceramic or on the backing).

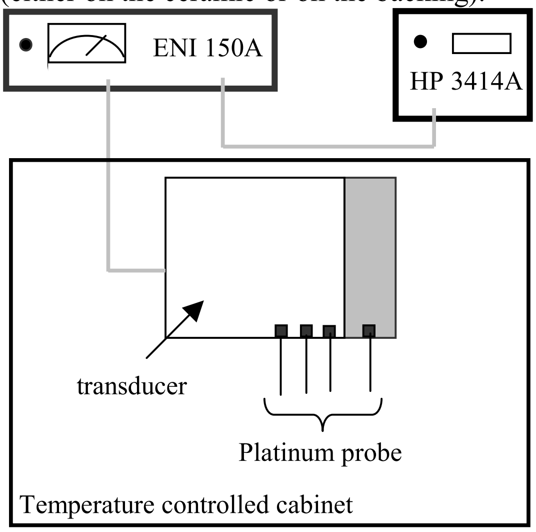

Figure 5: experimental set-up

For short time durations, one can reasonably assume that there is no heat exchange with the surrounding medium. At first, the absorbed energy will be converted into heat and will increase the temperature of the transducer. The temperature was measured on the ceramic as function of time when excited by a 1.15 MHz, 1.22 W quasi-continuous sinusoidal wave. This experimental curve was compared to theoretical prediction (equation 1), shown in figure 6. A good agreement is found. Results are as close as 0.1°C/s. It can be noticed that here the heat capacity of the ceramic was taken at 1200 J/K/kg which is much larger than the value given by the manufacturer (around 400 J/K/kg). The contact between the platinum probe and the ceramic is not perfect, which explain this discrepancy.

Knowing the current entering the transducer, this experiment can be conducted with frequency variations in order to experimentally determine the loss resistance in each part of the transducer.

Figure 7 shows theoretical and experimental equivalent loss resistances as a function of frequency. Here again a good agreement between theory and experiment is found which shows the validity of the model.

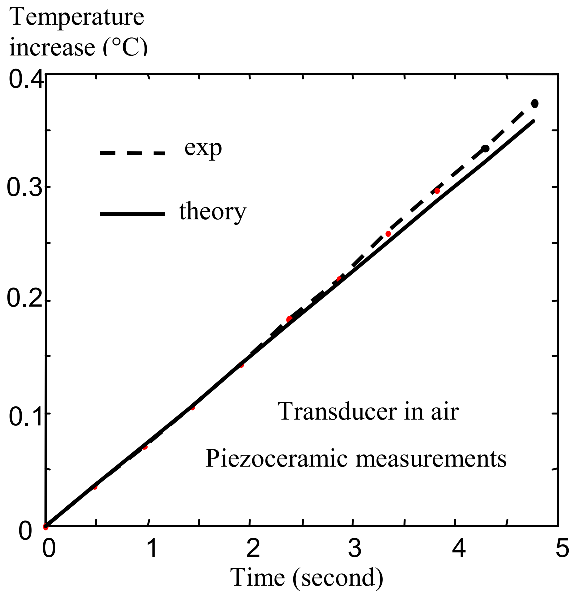

Figure 6: experimental and theoretical temperature increase as function of time

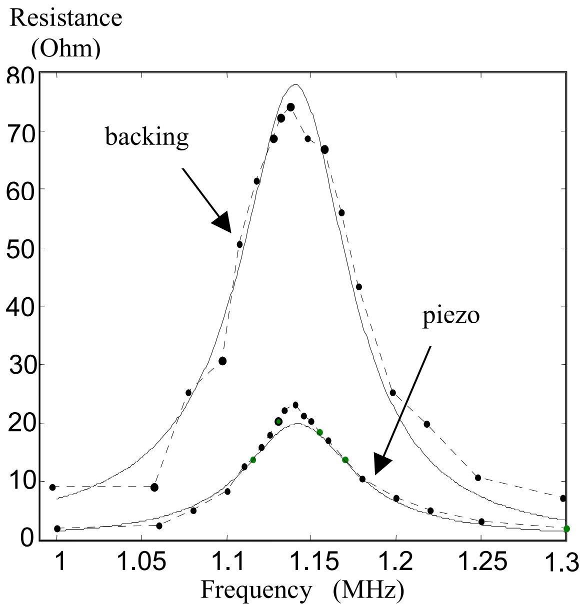

Figure 7: experimental equivalent loss resistance for the backing and the piezoceramic (dotted line: experiment, solid line: theory).

Now when the transducer is loaded by water, temperature measurements on the edge of the transducer are no longer possible with the experimental set up. The equivalent radiation loss resistance, $R_a(f)$, was thus measured in a water tank with standard electronic meters using the formula:

$$R_a = \frac{1}{2}\left|H_{tr}(f)\right|.\left|Z_{elec}(f)\right|$$

Where $\left|H_{tr}(f)\right|$ is the modulus of the transfer function of the transducer corrected for diffraction and $\left|Z_{elec}(f)\right|$ is the modulus of the electrectrical input impedance. Here again, a good agreement is found between theory and experiment (figure 8).

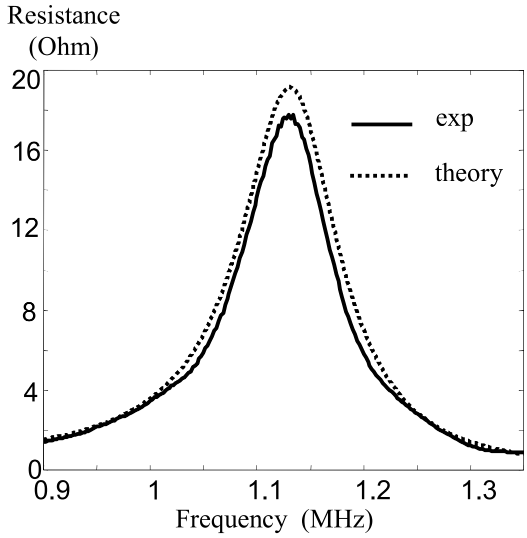

Figure 8: equivalent radiation resistance

Based on these results, it is possible to establish the temperature source profile in the transducer. According to the hypothesis that acoustic waves are instantaneously created, the acoustic wave velocity is much greater than thermal wave velocity. This result can be inserted in a thermal diffusion and heat exchange model that will calculate the temperature increase of the transducer in steady state [4]. Partial differential equations have been used to assess this problem and it was then possible to calculate the temperature field in the transducer in permanent regime. Figure 9 shows the theoretical and experimental temperature measured along the backing for a 4 MHz transducer that consists in a PZ 26 ceramic manufactured by Ferroperm glued on a epoxy backing.

In the backing, the temperature profile is non-uniform and decreases along the thickness. Close to the ceramic the temperature increase is 4 °C and corresponds to the temperature rise predicted by the theoretical model

Conclusion and perspectives

In this paper, we have proposed an analytical model to calculate the energy dissipation in each transducer element. First measurements in thermal transient regime for a transducer in air were carried out and show a good agreement with theory. Moreover, we have coupled this model to a heat diffusion model to obtain the theoretical temperature field for a transducer in air in thermal steady state. This calculation was confirmed by measurements. In the future, we will continue measurements for a transducer in water, and for a transducer excited by short electrical pulses.

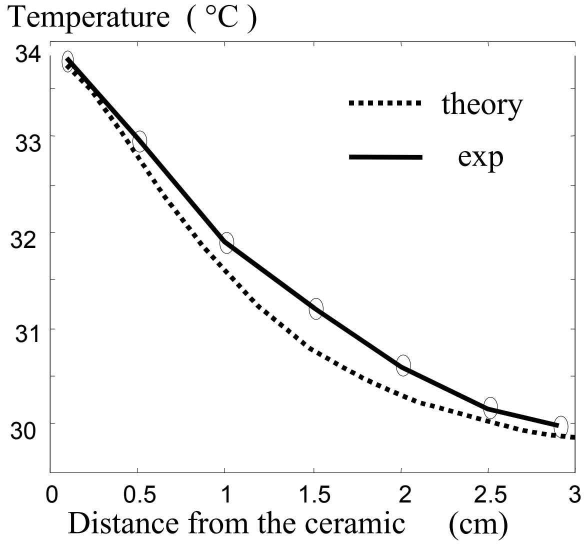

Figure 9: Experimental and theoretical temperature rise along the backing, (frequency: 3.84 MHz, delivered power: 0.1W)

Authors wish to thank Marion Bailly for ultrasonic transducers manufacturing.

This work was supported by European commission : LEAF project G5RD-CT62001-00431

References

[1] N. Abboud and *al*, In the proc. of 1997 IEEE Ultrasonics symposium, pp 895-900.

[2] W.P. Mason in Dieulesaint et Royer, tome 2 Masson ed Paris 1999.

[3] Guy Feuillard, Ph D thesis, university of Tours, 1993.

[4] Feynman, electromagnetisme 1, InterEditions ed, Paris 1979.