Double element ultrasonic transducer modelling with VHDL-AMS for lossy piezoceramic

Rachid Guelaz, Djilali Kourtiche, Rahma Belakhdar, Mustapha Nadi, Patrice Roth
Laboratoire d'Instrumentation Electronique de Nancy,
Université Henri Poincaré Nancy 1, B.P. 239 54506 Vandoeuvre Les Nancy
Rachid.Guelaz@lien.uhp-nancy.fr

Abstract

This paper presents a double element piezoceramic transducer modelling coupled with its electronics with VHDL-AMS referenced IEEE 1076.1. Piezoceramic double element is used for its sensibility at two different frequencies and dedicated to harmonic generation measurement in non linear ultrasonic domain. It was composed by a first element with a piezoceramic ring structure vibrating at a frequency of 2,25 MHz in thickness mode. The second element is stuck into the center of the first. This geometrical form is a disc vibrating at 4,5 MHz in thickness mode too. Transducer modelling with electronic and acoustic environment are studied with electrical and mechanical losses of the piezoceramic material. Transducer is implemented into VHDL-AMS with the Redwood model based on the piezoelectricity equations. To estimate transducer performance, we simulate pulse voltage response for each element. Results obtained for a P188 piezoceramic transducer show that transducer losses must be take into account in performance evaluation.

Keywords: ultrasonic, VHDL-AMS, piezoceramic, double element, losses

1 Introduction

Since few years Micro-Electro-Mechanical Systems (Mems) technology for ultrasonic measurements is studied. Two ultrasonic transducer types were developed : CMUT (Capacitive MicroMachined ultrasonic technology) and PMUT (Piezoelectric Micro-Electro-Mechanical Ultrasonic technology). This technology are considered as SOC (System On Chip) where transducers and their electronics are implemented in VHDL (Very High speed integrated circuits Hardware Description Language). VHDL-AMS language is appropriate for ultrasonic microsystems methodology conception because it could take into account all the transducer environment included microelectronic stimulation and acoustic load. In our simulation electronic stimulation is a pulse generator based on the use of MOSFET transistor (0,8µm) technology. Ultrasonic transducer is a double element implemented in VHDL-AMS [1] with the piezoceramic Redwood model with their mechanical and electrical losses [2]. Acoustic medium is assimilated to a transmission line [3] and implemented in VHDL-AMS language. We have simulated the global system in pulse-echo mode : a transducer generate an ultrasonic wave which is reflected by a metallic material into water. The electrical signal is compared with and without losses.

1.1 The double element transducer

Piezoelectric ceramics are frequently used for the ultrasonic transducers because they have a significant electromechanical coupling coefficient and stable physical characteristics. In our application, transducer is composed by a disc and a ring vibrating in thickness mode presented by the figure 1.

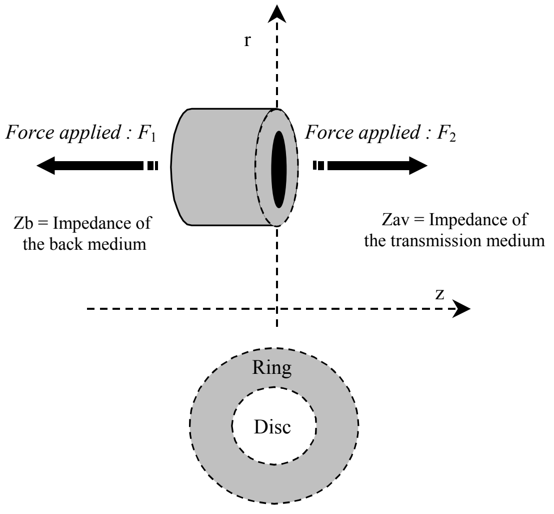

Figure 1: Ultrasonic piezoceramic double element transducer vibrating in thickness mode

1.1.1 Piezoceramic disc theory

Each element is governed by piezoelectricity equations which behaviour could be implemented into a matrix form where forces, velocities, voltage and current appear. For the disc two equations characterize the one-dimensional piezoelectricity of ceramic which are derived from Gibb's potential using Taylor series expansion. The stress T_3 applied on the two faces of the piezoelectric disc vibrating in thickness leads to the reverse piezoelectricity :

$$T_3 = C_{33}^D S_3 - h_{33} D_3 \tag{1}$$

where C_{33}^D is the elasticity modulus with null field or constant displacement, S_3 is the relative deformation. h_{33} is a piezoelectricity constant and D_3 is the electric displacement field given by relation (2)

$$D_3 = I/(jwA_d) \tag{2}$$

where I is the electrical current into the disk, A_d is the disc area and $w=2.\pi.F$ is the pulsation with F the frequency. The direct piezoelectricity formula is described by relation (3)

$$E_3 = -h_{33} S_3 - \beta_{33}^S D_3 \tag{3}$$

where $E_3=V_3/e$ is the electric field, β_{33}^S is a dielectric factor at constant deformation, V_3 is the input voltage and e is the ceramic thickness. The equations (1) and (3) with considering stress applied on the ceramic faces lead to a transfer matrix form (4) which describes the global behaviour between the electric excitation port and the two acoustic ports.

$$\begin{bmatrix} F_1 \\ F_2 \\ V_3 \end{bmatrix} = -j \begin{bmatrix} \frac{Z_T A_d}{\tan\left(w\sqrt{\frac{\rho}{C_{33}^D}}e\right)} & \frac{Z_T A_d}{\sin\left(w\sqrt{\frac{\rho}{C_{33}^D}}e\right)} & \frac{h_{33}}{w} \\ \frac{Z_T A_d}{\sin\left(w\sqrt{\frac{\rho}{C_{33}^D}}e\right)} & \frac{Z_T A_d}{\tan\left(w\sqrt{\frac{\rho}{C_{33}^D}}e\right)} & \frac{h_{33}}{w} \\ \frac{h_{33}}{w} & \frac{h_{33}}{w} & \frac{1}{wC_0} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ I_3 \end{bmatrix} \tag{4}$$

where v_1 and v_2 are the acoustic particles velocities at the front and the back faces of the disk, w is the pulsation, F_1 and F_2 are the acoustic forces at the transducer surfaces, ρ is the material density, Z_T is the acoustic impedance of ceramic material and C_0 is the capacitance value of the disk, I_3 is the electrical current.

1.1.2 Piezoceramic ring theory

The ring element is described in [4] and presented by figure 2. Forces and velocities noted F_i and v_i are present on each ring faces.

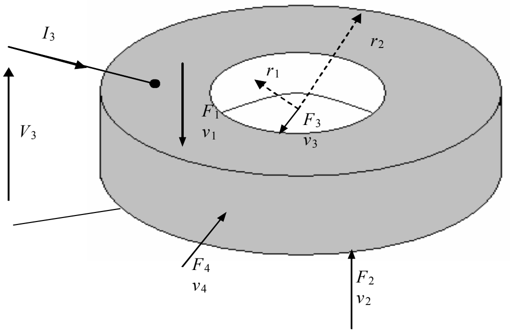

Figure 2: Piezoceramic ring

We consider r_1 and r_2 respectively the internal and the external radius and the global electrical displacement field D is expressed by

$$D = I/(jwA_r) \tag{5}$$

where I_1 is the electrical current into the ring and $A_r=\pi.(r_2^2-r_1^2)$ is the ring effective area. In our study we consider F_3, v_3 and F_4, v_4 null because the ring is stuck into a Plexiglas structure and the central disk vibrate only in thickness mode. So the global behaviour of the ring is the same that the disk behaviour. The difference is the effective surface A_d and A_r of each element in contact with the acoustic load. The ring behaviour is described by the relation (6).

$$\begin{bmatrix} F_1 \\ F_2 \\ V_3 \end{bmatrix} = -j \begin{bmatrix} \frac{Z_T A_r}{\tan\left(w\sqrt{\frac{\rho}{C_{33}^D}}e\right)} & \frac{Z_T A_r}{\sin\left(w\sqrt{\frac{\rho}{C_{33}^D}}e\right)} & \frac{h_{33}}{w} \\ \frac{Z_T A_r}{\sin\left(w\sqrt{\frac{\rho}{C_{33}^D}}e\right)} & \frac{Z_T A_r}{\tan\left(w\sqrt{\frac{\rho}{C_{33}^D}}e\right)} & \frac{h_{33}}{w} \\ \frac{h_{33}}{w} & \frac{h_{33}}{w} & \frac{1}{wC_0} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ I_3 \end{bmatrix} \tag{6}$$

1.2 The transducer modelling with VHDL-AMS

The integration of the transfer matrix (4) and (6) into an electric scheme is given by the Redwood [5] electrical model represented by figure 3 for one element.

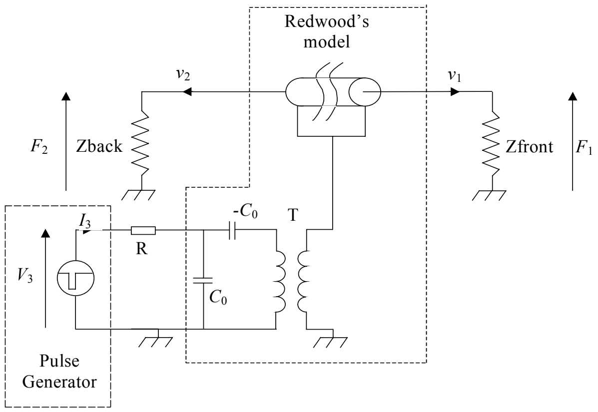

Figure 3: Redwood electric model

The model is divided in two parts. First is the electrical port which is composed by the capacitors C_0 and $-C_0$ that represent the capacitance motional effect. The second part is composed by the two acoustic ports. One is in contact with the back medium and the other is in contact with the propagation medium. Ceramic layer is represented by an electric propagation line. An ideal electro-acoustic transformer is integrated with a ratio corresponding to the transducer characteristic parameter. Transducer modelling with VHDL-AMS language is based on writing of the different equations of the Redwood scheme elements. Each circuit branches of the circuit (Figure 3) is transposed in VHDL-AMS code.

The VHDL-AMS model of the transducer is divided in three parts. First is the declaration of the *entity* which is composed by the physical characteristics of the transducer and the different *Terminals* used to connect it to electronic stage and acoustic load. Each *Terminals* are depends of the physical nature of the relation to be implemented to describe the element. Syntaxes noted “Electrical” and “Kinemativ_v” are respectively used to describe electrical and ultrasonic elements nature. The third part of the writing model is the declaration the *Architecture* which established the physic laws in correspondence to the element mathematical relation between each *Terminals*.

VHDL-AMS code of the transducer :

```
ENTITY Redwood IS
  GENERIC (Co,kt,Zo,td : real);
  PORT (TERMINAL p, m : electrical;
  TERMINAL t11,  t22, km: kinematic_v);
END ENTITY Redwood;

ARCHITECTURE bhv OF Redwood IS
Terminal  p1 : electrical;
Terminal t1,t1x,t2x : kinematic_v;
QUANTITY v1 across i1 through p TO m;
QUANTITY v2 across i2 through p TO p1;
QUANTITY vte across ite through p1 TO m;
QUANTITY pti across uti through t1 TO km;

BEGIN
  i1 == Co * v1'dot;
  i2 == -Co * v2'dot;
  pti == kt * vte;
  uti == -ite/kt;

 ceramic  :  entity  work.AcousticLayer  (bhv)
generic map (Zo,td)  port map (t11, t1,t22, t1) ;

END ARCHITECTURE bhv;
```

In this code, propagation on ceramic is assimilated to the electric line propagation behaviour. The model suggested below is thus consider to an acoustic propagation medium in which an incident ultrasonic wave is delayed of a *Td* time which corresponds to the flight time of the acoustic wave in material. This flight time is related to the relation *Td = co.e* with *co* the sound speed in the medium and *e* the thickness. *Z* is the characteristic acoustic impedance. This model corresponds to the electric equivalent circuit of Branin [6] presented by figure 4.

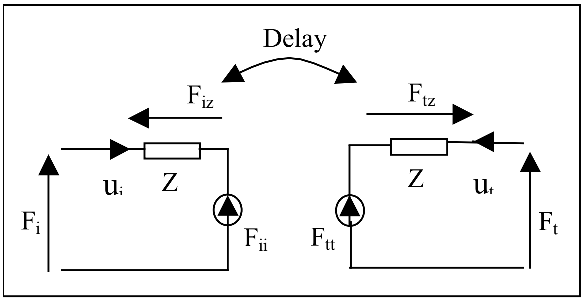

Figure 4: Equivalent electric diagram of the acoustic linear propagation in a medium without losses.

Indices *i* and *t* referred respectively to the incident part and transmitted part of the transmission line. Notation *u* referred to velocities in the medium, *F* to Forces. F_{ii}, F_{iz}, F_{tt} and F_{tz} are defined in the VHDL-AMS model with the integration of the delay *Td*. This propagation line model assimilated to a medium layer subjected to incident wave is modelled by the following writing:

```
ENTITY AcousticLayer IS
GENERIC  (Zo,Td    : REAL);
PORT        (TERMINAL p1,m1,p2,m2  : Kinematic_v);
END AcousticLayer;

ARCHITECTURE bhv OF AcousticLayer IS

terminal t11, t22 : Kinematic_v;
QUANTITY Fi ACROSS p1 TO m1;
QUANTITY Ft ACROSS p2 TO m2;
QUANTITY Fii ACROSS uiz THROUGH t11 TO m1;
QUANTITY Fiz ACROSS ui THROUGH t11 TO p1;
QUANTITY Ftz ACROSS ut THROUGH t22 TO p2;
QUANTITY Ftt ACROSS utz THROUGH t22 TO m2;

BEGIN

Ftt == Fi'DELAYED(Td) - Ftz;
Fii == Ft'DELAYED(Td) - Fiz;
Fiz == (uiz + utz'DELAYED(Td))*Zo/2.0;
Ftz == (utz + uiz'DELAYED(Td))*Zo/2.0;

END ARCHITECTURE bhv;
```

The acoustic propagation into ceramic layer is next modelled with mechanical losses $tan(\gamma_m)$ referenced in [2]. Pressure *P* and velocity *v* propagation equations are described with relation (7) and (8) with propagation constant.

$$\frac{d^2P}{dz^2}=\gamma^2P \qquad (7)$$

$$\frac{d^2 v}{dz^2} = \gamma^2 v \tag{8}$$

With z the axe propagation, γ the propagation constant. Solutions of the equations (7) and (8) is described by relations (9) and (10).

$$P(z) = P_i\, e^{-\gamma . z} + P_r\, e^{-\gamma . z} \tag{9}$$

$$v(z) = v_i\, e^{-\gamma . z} + v_r e^{-\gamma . z} \tag{10}$$

The acoustic layer with losses integration is described by this code :

```
ENTITY LossyAcousticLayer IS
  GENERIC  (Zo,Td,tangama    : REAL);
  PORT     (TERMINAL p1,m1,p2,m2  : Kinematic_v);
END LossyAcousticLayer;

ARCHITECTURE bhv OF LossyAcousticLayer IS

  TERMINAL t1x,t2x : Kinematic_v;

  QUANTITY V1r ACROSS p1 TO m1;
  QUANTITY V2r ACROSS p2 TO m2;
  QUANTITY V1xr ACROSS I1xr THROUGH t1x TO m1;
  QUANTITY V1x ACROSS I1x THROUGH t1x TO p1;
  QUANTITY V2x ACROSS I2x THROUGH t2x TO p2;
  QUANTITY V2xr ACROSS I2xr THROUGH t2x TO m2;

BEGIN

V2xr == (V1r'DELAYED(Td)*exp(-3.14*tangama*1.0e-3) - V2x);

V1xr == (V2r'DELAYED(Td)*exp(-3.14*tangama*1.0e-3) - V1x);

V1x == (I1x + I2x'DELAYED(Td)*exp(-3.14*tangama*1.0e-
3))*Zo/2.0;

V2x == (I2x + I1x'DELAYED(Td)*exp(-3.14*tangama*1.0e-
3))*Zo/2.0;

END ARCHITECTURE bhv;
```

Electrical losses is well known to be the resistance leak of the ceramic capacitance considered as a resistance which depends on the frequency described by relation (11)

$$R_e = \frac{1-k_t^2}{C_0.\tan(\delta_e)} \cdot \frac{1}{\omega} \tag{11}$$

With k_t the coupling factor in thickness mode, C_0 is the capacitance of the ceramic, *tan(δe)* is the losses factor and *w* the pulsation.

2 Microelectronic pulse generator

Electric stimulation of transducer in ultrasonic imaging system is a positive pulse voltage during a time corresponding the transducer frequency resonance. Pulse generator proposed is based on the use of the MOSFET technology because of the need of sufficient power. Impedance coupling between the pulse generator and the transducer input impedance must be arranged to obtain the better electric power transfer. Figure 5 presents the electric scheme of the pulse generator.

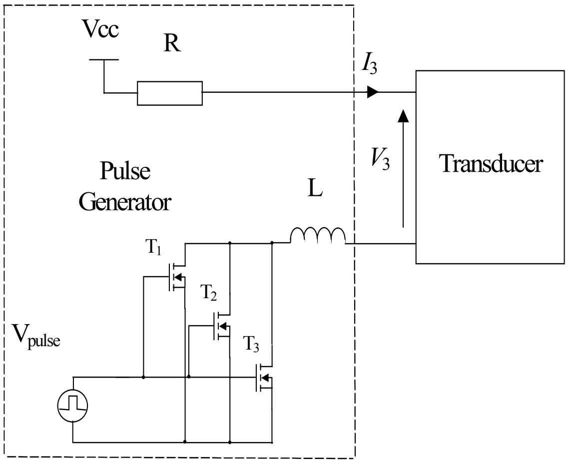

Figure 5: Microelectronic pulse generator with Mosfet transistor coupled to the transducer.

V_{pulse} is an electrical signal generated by an external source. L is an inductor used for impedance adaptation between the pulse generator and the transducer. V_3 is the voltage issue to pulse generator. R is a 10 kOhms resistance.

The principle of the pulse generator is a commutation system activated by an external signal. The maximal voltage is 20 Volts in our study. To perform commutation, we have used three transistors. Each transistor is characterized by its weight W_T = 140 µm and length L_T = 0,8 µm.

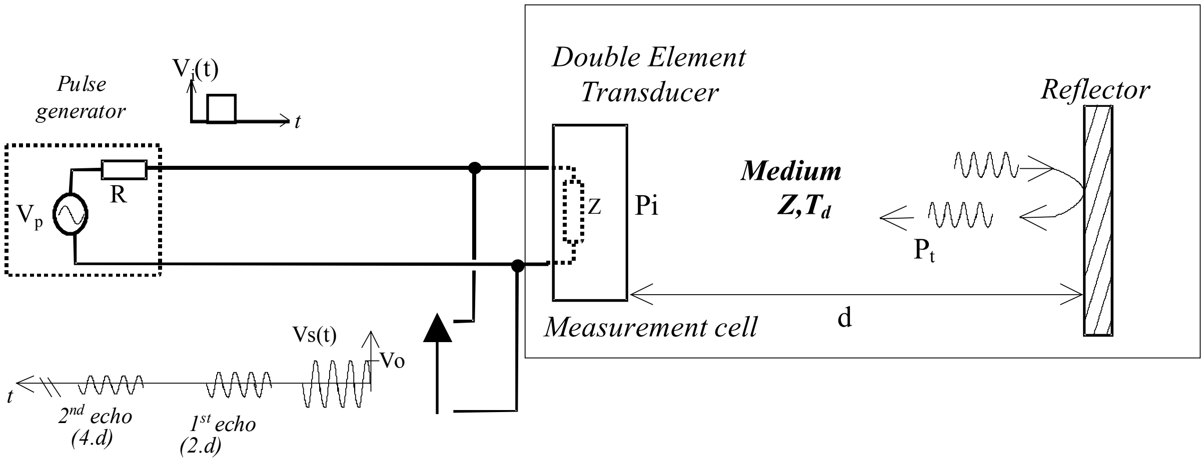

Figure 7: Scheme of the ultrasonic cell for pulse-echo simulation

Table 1: Transducer Acoustic Characteristic

Parameters	Quantity	Ring	Disc
f_0	Frequency resonance	2,25 MHz	4,5 MHz
A	Area	$132,73\ mm^2$	$132,73\ mm^2$
E	Thickness	1 mm	0,5 mm
Zt	Acoustic impedance	34,9 MRayls	34,9 MRayls
Va	Sound speed	4530 m/s	4530 m/s
Co	Capacitor of the ceramic disk	759 pf	1510 pf
E_{33}	Dielectric constant	650,0	650,0
kt	Thickness coupling factor	0,49	0,49
h_{33}	Piezoelectric Constant	$1,49.10^{+9}$	$1,49.10^{+9}$
$tan(\delta e)$	Dielectric loss factor	2%	2%
$tan(\delta m)$	Mechanical loss factor	1,25%	1,25%

3 Simulation results

We performed simulation with a pulse-echo system modelling presented by figure 7. The simulation tool is Adv_Ms of Mentor Graphics. A voltage pulse is generated with 20 Volt amplitude during a time T_d which correspond to the relation $T_d = 1/(2.f_0)$ with f_0 the resonance frequency of each element of the transducer. The ultrasonic wave is transmitted to a medium characterized by its acoustic impedance *Z* and its propagation time T_d. A metallic material is placed at the end of the medium as an ultrasonic reflector. Transducer characteristics are regrouped in table 1. Water is used as propagation medium. Figures 8 and 9 represent results obtained with the ring element. Figures 10 and 11 show results obtained with disc element.

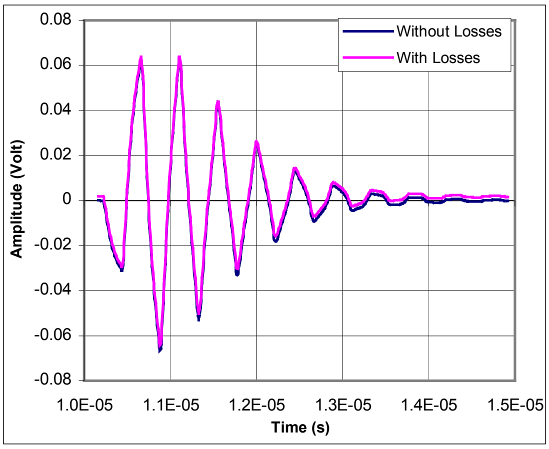

Figure 8: Results obtained with the ring element vibrating at 2,25MHz in water.

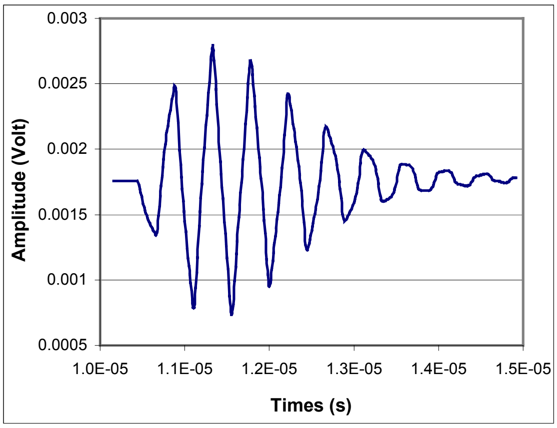

Figure 9: Difference between with and without losses with the ring element vibrating at 2,25MHz in water

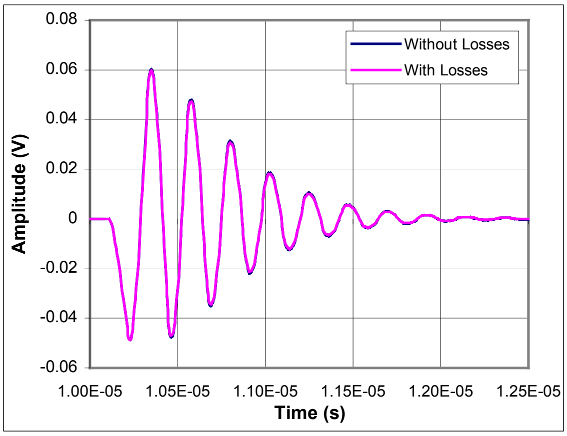

Figure 10: Results obtained with the disc element vibrating at 4,5MHz in water.

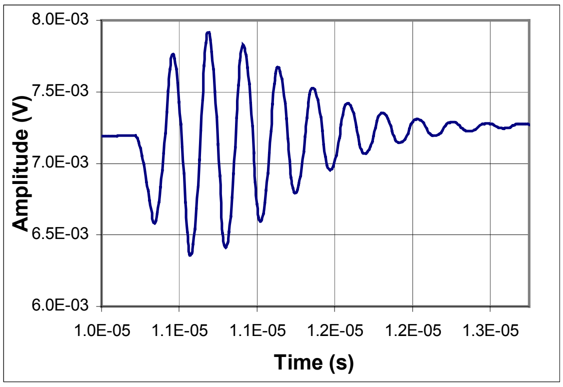

Figure 11: Difference between with and without losses with the disc element vibrating at 4,5MHz in water

Results obtained with the ring element vibrating at 2,25 MHz show a maximum error of 3% and 1,7% for the disc element vibrating at 4,5MHz. In the two cases, wave forms are similarly the same. More the frequency resonance is low and more the difference is highlighted.

Conclusion

This paper presents a complete approach of ultrasonic systems modelling with electronic, transducer and medium behaviour description. Double element transducer based on piezoceramic material is implemented with the Redwood model. Dielectric and mechanical losses has take into consideration with propagation theory. Simulation of a pulse-echo ultrasonic system show difference between losses consideration. More frequency resonance is low and more error is highlighted. Perspectives of this work is to implement microelectronic system and double element transducer on the same chip with a VHDL-AMS validation simulation.

References

[1] Guelaz, R., “Double element ultrasonic piezoceramic transducer modeling with VHDL-AMS: application to B/A nonlinear ultrasonic parameter measurement in pulse-echo mode”, *Electronic Journal “Technical Acoustic” <http://webcenter.ru/~eeaa/ejta>*,10(2005).

[2] Chen Y.C., “PSPICE implementation for designing the acoustical matching layers of ultrasonic piezoelectric transducers”, IEEE Ferroelectrics, pp.153-173 (1999).

[3] Guelaz R., Kourtiche D., Hervé Y., Nadi M., “Modeling of the ultrasonic nonlinear propagation with VHDL-AMS”, *in Proceedings of FDL’04: Forum on Specification and Design Languages*, (2004)

[4] Brissaud M.,” Characterization of piezoceramics ”, *IEEE Trans. Ultrason., Ferroelect., Freq. Control.,* v.38, pp 603–617, 1991

[5] M. Redwood M., ”Transient performance of a piezoelectric transducer”, *J. Acoust. Soc. Amer.,* v.33, 527-536.(1961).

[6] Branin F., “Transcient analysis of lossless transmission lines”, *in proceedings of IEEE* v.55, pp. 2012-2013. (1967).