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Modelling of PZT/PVDF Ultrasonic Transducer with VHDL-AMS for Medical Applications

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Abstract: The one indispensable part of a diagnostic imaging system is the transducer. Multi-resonance transducer using lead zirconate titanate piezoelectric ceramics (PZT) was designed several years ago for dual Doppler and B mode use. As polymer (PVDF) material being popular in medical ultrasound, there is possibility of combining the two materials into a single structure in order to obtain a multi-frequency transducer for different clinical diagnostic. For this study, the model is implemented with the VHDL-AMS behavioral language. The simulations approaches presented in this work are based on the electrical KLM model and its parameters are deduced from the transducer electroacoustic characteristics.

Keywords: Modeling, Ultrasonic transducer, Ceramic, Polymer, VHDL–AMS.

1. Introduction

The ultrasound (sonography) technique has become the most common medical image, because of its higher performance and lower cost devices. Over the past 15 years, the parallel development of image systems and piezoelectric transducers allowed the acquisition of good image resolution, which has emerged as an essential tool for establishing diagnosis in many cases of pathologies. The ultrasonic tomography B mode and the Doppler mode are widely used in clinical diagnostic. For each mode, the sonographer that is used for different ultrasonic probe: one for Doppler and the other for B mode is considered as a less convenient method. Hence the necessity of a single transducer covering a wide frequency band becomes important. An example of work in dual resonances ultrasonic probe for medical application was introduced in [1]. They proposed two layers ceramics with opposite poling direction and controlled relative electromechanical coupling factor in the fundamental and the second harmonic by adjusting its thickness ratio. They obtained dual frequencies of 3.75 MHz and 7.5 MHz (dual peaks of the power spectrum). As a result, a high resolution B mode and a high sensitivity Doppler mode image with one ultrasonic probe instead of two different probes had been achieved.

Lead zirconate titanate piezoelectric ceramics (PZT) are frequently used for ultrasonic transmitting and receiving materials. This is because a PZT ceramic has a large electromechanical coupling factor that represents the conversion efficiency between electrical and mechanical energy. Polymers materials like the polyvinylidene fluoride (PVDF) is largely used in the medical imaging, as it is tough, flexible and is readily available in the form of thin films. Its close acoustic impedance match to water and living tissues and their high electrical impedance for high frequency system is an advantage in biomedical applications. Combining the two materials, allows us to generate a new multi-frequency transducer with more performances than ceramic or polymer conventional transducer.

Modeling and simulation of ultrasonic transducers systems is a challenging task due to the presence of multi-physics effects such as electrical and mechanical effects and their interaction. The electromechanical interaction, represented by electrical equivalent circuits, was first introduced by Mason [2]. He proposed an exact equivalent circuit that separated the piezoelectric material into an electrical port and two acoustical ports through the use of an ideal electromechanical transformer. The problem with the model is that it required a negative capacitance at the electrical port. Redwood [3] improved this electromechanical model by incorporating a transmission line, making possible to extract useful information on the temporal response of the piezoelectric component. But it cannot model multilayered transducers. The KLM model was presented by Krimholtz, Leedom and Matthai [4]. This analogous circuit consists on a frequency-dependent network. It includes a transformer connected to the middle of a transmission line. This model has been widely used in the medical imaging to design high frequency transducers. This design is advantageous in applications such as acoustically cascaded ones.

Different approaches were proposed to predict the piezoelectric transducer behavior such as a numerical resolution of piezoelectric equations. Another approach is based on the equivalent electrical circuit simulation using an electric simulator like SPICE (Simulation Program with Integrated Circuit Emphasis). However SPICE presents some limitations such as inaccuracy analysis related to the intrinsic algorithms calculation which often privilege the speed of execution to the detriment of the accuracy. In addition, nonlinear components models used by SPICE sound very approximate because they do not hold account of the real physical parameters of models. The use of other tools of analysis, example, the tool for behavioral description of type VHDL-AMS (Very High speed integrated circuit Hardware Description Language Analogue and Mixed Signal) can be a solution with the limitations caused by the use of Spice simulator.

2. Theory of the Piezoelectric Ultrasonic Transducer

The piezoelectric material is the principal element in an ultrasonic transducer. The piezoelectric materials have the advantage compared to the other systems of presenting good performances and to be available in very diverse geometries. These materials are generally appeared as a disc, a ring or plate. Our piezoelectric element has the characteristic to vibrate in thickness mode, on only one direction axis (z). This modelling study is thus limited to one geometrical dimension (1-D), with the boundary conditions at the acoustic ports Fig. 1 [5].

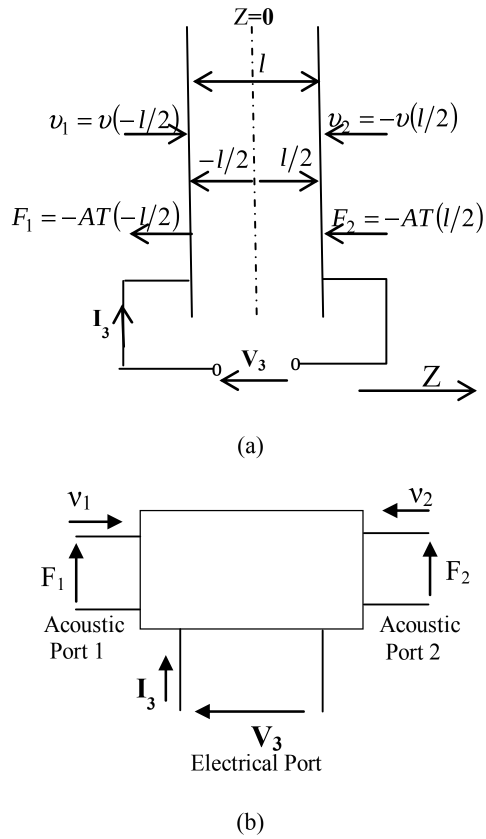

Fig. 1. (a) Piezoelectric plate of thickness; (b) representation as a three port system.

The external force applied to the piezoelectric material at the surface is:

$$F = -AT, \tag{1}$$

where A is the area of the transducer and T is the internal stress.

Let's consider e the thickness of the piezoelectric plate and V_3 is the excitation voltage. F_1 and F_2 presented the forces transmitted to the propagation medium on the front and back face of the transducer. v_1 and v_2 are the acoustic particles velocities at the front and the back faces of the transducer. In these conditions, two equations characterize the one-dimensional piezoelectricity of piezoelectric plate. If we defined T_3 the stress applied on the two faces of the piezoelectric plate vibrating in thickness leads to the reverse piezoelectric. We can write then:

$$T_3 = C_{33}^D S_3 - e_{33} E_3 \tag{2}$$

With C_{33}^D is the elasticity modulus with constant field. S_3 is the relative deformation. e_{33} is the Piezoelectric constant. E_3 is the electric field. The electric displacement field can be calculated using the Equation (3):

$$\mathrm{D_3 = e_{33} S_3 + \varepsilon_{33}^S E_{33}} \tag{3}$$

With ε_{33}^{S} is the dielectric constant at a constant deformation.

The Equations (2) and (3) with considering stress applied on the piezoelectric plate faces lead to a transfer matrix form (4) which describes the global behavior between the electric excitation port and the two acoustic ports.

$$\begin{bmatrix} F_1 \\ F_2 \\ V_3 \end{bmatrix} = -j \times \begin{bmatrix} Z_T\left(\tan\left(w\sqrt{\frac{\rho}{C^D}}e\right)\right)^{-1} & Z_T\left(\sin\left(w\sqrt{\frac{\rho}{C^D}}e\right)\right)^{-1} & h_{33}.w^{-1} \\ Z_T\left(\sin\left(w\sqrt{\frac{\rho}{C^D}}e\right)\right)^{-1} & Z_T\left(\tan\left(w\sqrt{\frac{\rho}{C^D}}e\right)\right)^{-1} & h_{33}.w^{-1} \\ h_{33}.w^{-1} & h_{33}.w^{-1} & \left(w.C_0\right)^{-1} \end{bmatrix} \times \begin{bmatrix} v_1 \\ v_2 \\ I_3 \end{bmatrix} \quad (4)$$

v_1 and v_2 (m/s) are the acoustic particle velocities at the front and the back faces of the plate, $\omega = 2\pi f$ is the electrical pulsation where f is the frequency, F_1 and F_2 are the acoustic forces at the transducer faces, ρ is the material density, Z_T is the acoustic impedance of the piezoelectric material, $h_{33} = e_{33}/\epsilon_{33}$ is the piezoelectricity constant and C0 is the capacitance value of the plate, and I3 is the electrical current.

3. Traditional Electro-Acoustic Model of Piezoelectric Element

The equivalent circuit of a thickness–mode piezoelectric transducer can be represented by the KLM model as shown in Fig. 2, where the electric part is composed of clamped capacitance C_0 is the static dielectric value resulting between the conductive layers of the ceramic, a second term of negative capacitance C' is a frequency dependent reactance which is negligible near resonance. The electro-acoustic transformer has a frequency dependent turns ratio Φ (the transformer ratio of electric voltage to mechanical force). The mechanical part of the KLM circuit is equivalent to an acoustical transmission line.

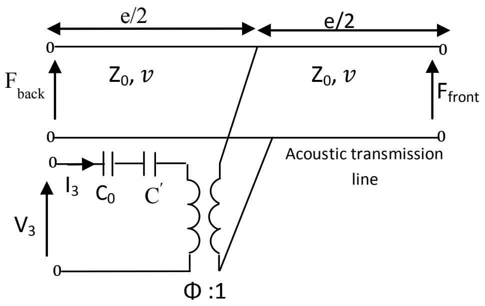

Fig. 2. KLM Equivalent circuit of a thickness - mode piezoelectric transducer.

The piezoelectric layer is in contact with the back medium and the other is in contact with the propagation medium. Transducer modeling with VHDL-AMS language is based on writing of the different equations of the KLM scheme elements.

The circuit parameters of the piezoelectric material are defined as follows [4]:

$$C_0 = \frac{\varepsilon_{33}^{S} A}{e}, \quad (5)$$

$$C' = \frac{C_0}{K_t^2 \mathrm{sinc}(\omega e/\pi v)}, \quad (6)$$

$$\Phi = \frac{2h\sin(\omega e/2v)}{Z_0 \omega}, \quad (7)$$

where ε_{33}^{S} is the permittivity coefficient at constant deformation, A and e are respectively the surface area and the thickness, ρ is the density, $v = v^D = (C_{33}^D/\rho)^{1/2}$ is the wave speed of compressional waves in the piezoelectric plate, K_t is the coupling factor, h_{33} is the piezoelectric constant, C_{33}^D is the elasticity modulus with field or constant displacement, $Z_0 = \rho v A$ is the acoustic impedance and ω is the angular frequency.

4. VHDL-AMS Behavioral Model of Transducer

The VHDL-AMS is an IEEE standard [6]. It was developed as an extension of VHDL to enable the modeling and simulation of circuits and analog and digital - analog mixed systems. VHDL-AMS is a superset of VHDL, which primarily means that the extensions made in VHDL-AMS retain the principles VHDL. VHDL-AMS offers five types of design units: the entity declaration, the architecture body, the declaration of configuration, the package declaration and the package body. The first three units allow the design description of the material aspect of a system, while the last two are used to group information that can be reused for the description of several different systems.

The VHDL-AMS implementation of the previous model Fig. 2 is divided in two parts. First is the declaration of the entity which is composed of the physical characteristics of the transducer and the different terminals used in connection. Each TERMINAL depends of the physical nature of the relation to be implemented to describe the element. Using the statements ELECTRICAL in the electrical domain and KINEMATIC_V in the acoustic domain. The second part of the model is the architecture which establishes the physic laws related to the mathematical relation between each terminal.

The model is divided in three parts. The first one is the electrical port which includes the capacitors C_0 and C'. The second part consists of an ideal electroacoustic transformer with a ratio Φ. The third part is the mechanical part; it is represented by an acoustic transmission line.

4.1. Modelling of the Electric Port

This electrical port is connected to a resistance R and a voltage source noted V_3. The study of the electrical and mechanical behavior of the transducer, including its frequency response, requires the presentation of a model in VHDL -AMS frequency source. The Frequency function is referenced to a frequency electric source described by a spectrum source. Libraries should be called before elements description.

```
LIBRARY disciplines;
USE disciplines. electromagnetic_system.all;
USE disciplines. kinematic_system.all;
LIBRARY ieee;
USE ieee.math_real.ALL;

ENTITY Source_AC
PORT (TERMINAL Vn,Vp: ELECTRICAL);
END Source_AC;
ARCHITECTURE bhv OF Source_AC IS
QUANTITY V3 ACROSS I3 THROUGH Vp to Vn;
QUANTITY Vac: real spectrum 1.0,0.0;
BEGIN
    V3== Vac;
END ARCHITECTURE;

ENTITY KLM ELECTRIC IS
GENERIC (C0: Real);
PORT (TERMINAL Vp, p1, p2, p11:
ELECTRCAL);
END ENTITY KLM ELECTRIC;
QUANTITY VC ACROSS IC THROUGH p1 to p2;
QUANTITY VC′ ACROSS Ic′ THROUGH p2 to p11;
BEGIN
IC0 == C0 * VC0 dot;
IC′ == C′ * VC′ ′ dot;
END ARCHITECTURE;
```

4.2. Modelling of the Electro-Acoustic Transformer

The electro-acoustic transformer with a ratio Φ make the coupling between the electric and the acoustic parts is modeled in an ideal form (Fig. 3). Its role is to transform the electric power into a mechanical power in the form of a wave pressure. The writing of the transformer with VHDL-AMS is given by two simple relations. The first one is the relation between the voltage Vt and the transmitted pressure Pt. The second one is the relation between the electric current I_3 and the acoustic velocity v in the medium [7].

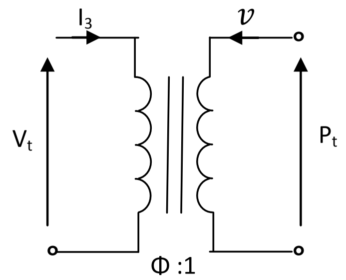

Fig. 3. Electro-acoustic transformer.

The VHDL–AMS implemented code of electro-acoustic transformer is as follows:

```
ENTITY Transfo IS
GENERIC (kt: real);
PORT (TERMINAL p11, m: electrical; TERMINAL:
p12, p22:kinematic_v);
END ENTITY Transfo;
ARCHITECTURE bhv OF Transfo IS
QUANTITY Vt across I3 through p11 TO m;
QUANTITY Pt across v through p12 TO p22;
BEGIN
    Pt ==Vt*kt;
    v == -I3/kt;
END ARCHITECTURE bhv;
```

4.3. Modelling of Acoustic Transmission Line

The mechanical part of the transducer is modelled by an acoustic transmission line. Therefore it is based on the analogy electroacoustic; the acoustic transmission line is equivalent to an electrical transmission line [8]. Table 1 shows the electroacoustic analogy.

The acoustic transmission line with VHDL–AMS language is assimilated to electric transmission line behavior without losses. The parameters of the transmission line is Z_0 (the acoustic impedance) and Td (delay time). They are calculated from the acoustic characteristics of the piezoelectric material used. With $Z0=Z_CA$, Z_C is the characteristic acoustic impedance and A is the area. $Td=e/v_0$, e is the thickness and v_0 represents the characteristic propagation celerity.

A transmission line has two ports which consist of a voltage source in series with a resistor. The voltage source is dependent on the present time minus the delay time.

Table 1. Electroacoustic analogy.

Acoustical		Electrical	
Parameter	**Unit**	**Parameter**	**Unit**
Sound Pressure (p)	$Kgm^{-1}s^{-2}$	Voltage (V)	V
Particle velocity (v)	ms^{-1}	Intensity (I)	A
Particle displacement (u)	m	Charge (Q)	C
Acoustic resistance (R_A)	$Pa.s/m^3$	Resistance (R)	Ω
Acoustic Compliance (C_A)	m^3/P_a	Capacitance (C)	F
Inertance (M_A)	$ms^{-2}N^{-1}$	Inductance (L)	H
Acoustic impedance (Z_A)	$Kgm^{-2}s^{-1}$	Impedance (Z)	Ω

The two equations for a transmission line are:

$$V_{(t1x.t1r(t))} = V_{(t2.t2r(t-td))} + Z_0 \times I_{(t2t2r(t-td))} \quad (8)$$

$$V_{(t2x.t2r(t))} = V_{(t1.t1r(t-td))} + Z_0 \times I_{(t1t1r(t-td))} \quad (9)$$

The VHDL–AMS implemented code of acoustic transmission line is as follows [9].

```
ENTITY Line IS
GENERIC (Z0,Td: real);
PORT (TERMINAL t1, t1r, t2, t2r: electrical);
END Line;
ARCHITECTURE t-line OF Line IS
TERMINAL t1x, t2x: electrical; two external nodes
QUANTITY v1r ACROSS t1 TO t1r;
QUANTITY v1x ACROSS i1x THROUGH t1 TO t1x;
QUANTITY v1xr ACROSS t1x TO t1r;
QUANTITY v2r ACROSS t2 TO t2r;
QUANTITY v2x ACROSS i2x THROUGH t2 TO t2x;
QUANTITY v2xr ACROSS t2x TO t2r;
BEGIN
v1xr == v2r' DELAYED (Td) + Z0*i2x' DELAYED (Td);
v2xr == v1r' DELAYED (Td) + Z0*i1x' DELAYED (Td);
END ARCHITECTURE t-line;
```

5. Hybrid Multi- Frequency Model

Piezoelectric equivalent model in Fig. 2 can be used for ceramic material as well as polymer material. Two identical circuits as Fig. 2 are combined, In order to build hybrid model (Fig. 4). One uses PZT-4 parameters from Table 2, while the other uses PVDF parameters from Table 3. The piezoelectric layers of hybrid model are connected in series both acoustically and electrically.

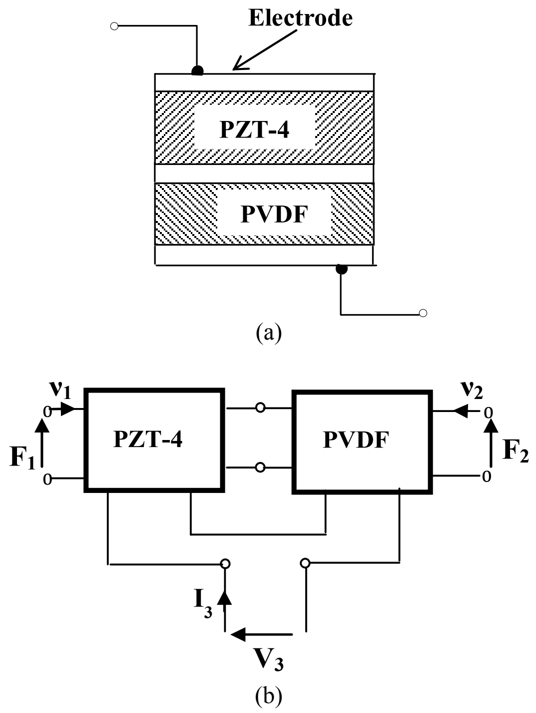

Fig. 4. (a) Hybrid transducer model; (b) Representation as a three port system.

5.1. Piezoelectric Ceramic Parameter

The ceramic PZT-4 which builds our transducer is a plate with thickness frequency 1 MHz, 2 mm thick and area 0.49×10^{-3} m^2. According to data from [10-11]. The parameters of piezoelectric ceramic element are shown in Table 2.

Table 2. Parameters of PZT-4 used in simulation.

Parameter	Definition	Value	Unit
ρ	Material density	7500	Kg/m^3
v_0	Acoustic velocity	3980	m/s
C_0	Capacitor	1435	PF
ε^s	Dielectric constant	5.86×10^{-9}	C^2/Nm^2
Z_C	Acoustic impedance	29.85	MRayls
K_t	Coupling factor	0.45	-
h_{33}	Piezoelectric constant	2.68×10^9	-

5.2. Piezoelectric Polymer Parameter

The piezoelectric polymer material used in our simulation is a 270 μm thick film; uniaxial poled with aluminum electrodes, 0.1 μm thick. Electrodes can be attached to PVDF in one of two ways: conducting adhesive using silver loaded epoxy, or mechanical contact via a crimp or fold. Several publications [12-13] have reported PVDF parameters have been compiled in Table 3.

Table 3. Parameters of PVDF used in Simulation.

Para-meter	Definition	Value	Unit
ρ	Material density	1750	Kg/ m^3
v_0	Acoustic velocity	2250	m/s
C_0	Capacitor	245	PF
ε^s	Dielectric constant	55.7×10^{-12}	C^2/Nm^2
Z_C	Acoustic impedance	3.92	MRayls
K_t	Coupling factor	0.127	-
h_{33}	Piezoelectric constant	1.52×10^9	-

6. Circuit for VHDL-AMS Simulation

When the model is being implemented into VHDL-AMS, it should be connected with signal source and medium model. The role of the acoustic impedance Zback on the back face of transducer is to damp the ultrasonic wave. It is fixed to 600 Mrayls in our simulation. The other branch (front face) of transducer is in contact with the propagation medium (Zfront). The propagation medium used in our simulation is the water at 25 °C can also be represented by a transmission line. Its parameters (Z0 and Td) are calculated from the acoustic characteristics of the propagation medium given by Table 4 [14].

Table 4. Propagation medium acoustic characteristics.

Propagation medium	Acoustic impedance	Acoustic speed
Water	1.49 (Mrayl)	1496 (m/s)

The resistor between the electrical transducer input and the voltage source R=50 Ω. Fig. 5 shows example of complete circuit for simulation.

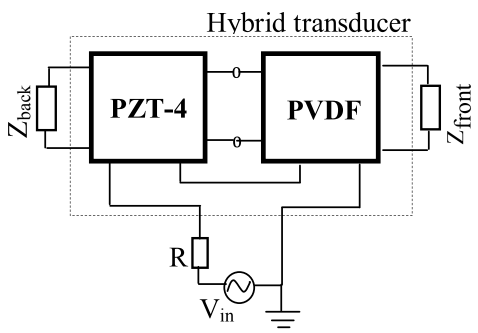

Fig. 5. Model circuit for VHDL-AMS simulation.

The frequency transducers response study is essential to predict the sensitivity of the system. To perform the transducer frequency analysis, we used a VHDL-AMS Testbench where a frequential source Vac of 1V is connected to the electrical input. Fig. 6 shows frequency response of hybrid transducer.

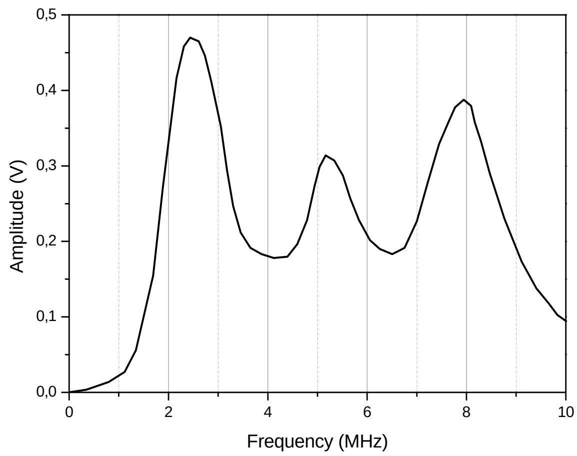

Fig. 6. Frequency response of transducer.

AC analysis was conducted to observe frequency behaviour from zero to 10 MHz. There are three peaks of power spectrums: at 2.4989 MHz, 5.2103 MHz and 7.9845 MHz. The first spectrum is higher than another, but for overall dB, bandwidth from 2 MHz to 9 MHz which covers the entire range of sonography frequency is considerable.

Fig. 7 and Fig. 8 shows respectively the electrical impedance of transducer and the impedance phase. This result shows a resonance frequency at about 1 MHz that corresponds typically to the acoustic value of the transducer.

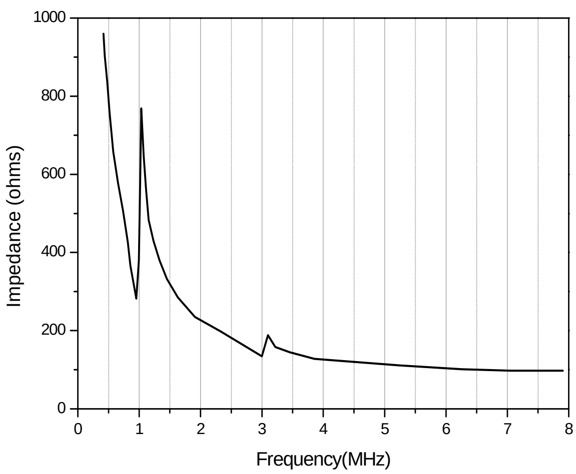

Fig. 7. Transducer impedance modulus Z.

7. Conclusions

In this paper, based on previous works a new approach of ultrasonic transducer modelling system is presented. The use of VHDL-AMS language shows the advantage to combine multi-physical domains. VHDL-AMS model of ceramic-polymer piezoelectric has been described. Simulation level shows that by hybridization, characteristics of both materials are providing a satisfying performance for multi-frequency transducer.

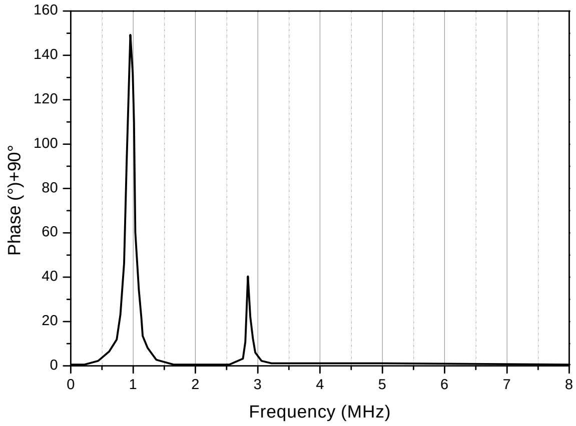

Fig. 8. Transducer impedance phase.

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