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MODELLING AND SIMULATION OF ULTRASOUND NON LINEARITIES MEASUREMENT FOR BIOLOGICAL MEDIUMS

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Abstract

We present an implementation of the nonlinear propagation in an ultrasonic measurement modeling with VHDL-AMS–IEEE-1046-1999 language . The system is dedicated to nonlinear mediums characterization by a compared method measurement. Usual modelling of ultrasonic transducers are based on electrical analogy and are not simulated in the global measurement environment. The ultrasonic transducer modelling proposed is simulated with the nonlinear acoustic load and electronic excitation. The nonlinear B/A parameter is used to characterize medium with a comparative method. The measurement cell is composed of two piezoelectric ceramic transducers which are implemented with the Redwood's electric scheme. The analyzed medium is placed between the transducers and modeled to take into account the nonlinear propagation with the B/A parameter. The usual transmission line model has been modified to take into account the nonlinear propagation for a one dimensional wave. Results obtained with simulation of mediums characterization with (blood, milk, liver and human fat tissue) showed good a modeling in agreement between modelling and experimental measurement, also a maximum error of about 12.5%.

1. INTRODUCTION

The ultrasonic imaging calls upon very advanced technologies in term of high-speed signal processing and conception of ultrasonic transducers matrix in nanotechnology methodology. The useful signal is generally the fundamental frequency of the resonance transducers. However recent studies show the interest of the harmonic frequencies analysis generated by the crossing of ultrasonic waves in biological environments. Works show the improvement of the image quality as in the case of the second harmonic imaging [1]. In addition to the image quality, the measurement method of the nonlinear parameter B/A makes it possible to envisage a mediums characterization. The integration of this parameter in ultrasonic system modelling is an essential stage of the measurement system conception study for multi layer biological environment analysis. Two types of methods make it possible to evaluate the nonlinearity parameter : the thermodynamics methods [2] and the finited amplitude methods [3]. The first is not credible for in vivo measurement because of the precise variation needed in environmental parameters such as the temperature or the pressure in tissues. The second method is more realist and consists in analyzing the harmonic wave propagation of the ultrasonic signal. The coupling of the various physical natures parts (electronics and acoustics) requires the use of mixed language such as VHDL-AMS IEEE 1076-1999 to determine precisely the influence of each part in the measurement system. Usual modellings of ultrasonic systems use an acoustic model medium assimilated to an electric propagation line without losses [4] and without nonlinear aspect. Our model based on this same theory of electric propagation line integrates the nonlinearity B/A parameter, by a recurrent formulation of the Burger's equation solution [5].

The measurement system modelling is based on a nonlinear medium excitation by an ultrasonic transducer vibrating at a fixed frequency fo. An identical transducer is placed at the end of the measurement cell and makes it possible to analyse the acoustic wave in the propagation axis of the transmitting source. The electric signal analysis of the receiver transducer is used to identify the acoustic signal at its fundamental frequency and its second harmonic by a fast Fourier transform. Parameter B/A is estimated by a comparative method [6] with water like reference medium and ethanol like analysed medium. The parameter B/A estimation shows a measurement system modelling adapted to the ultrasonic medium characterization study.

2. THE MEASUREMENT SYSTEM MODELLING

2.1 The measurement principle of a comparative method

The measurement system principle for study the ultrasonic characterization is presented in figure 1. A transducer emits an acoustic wave at a frequency fo through medium. A receiving transducer vibrating at the same frequency fo in a first case is placed at the end of the measuring cell. In a second case, we study the response obtained with a transducer vibrating at 2fo in order to improve the sensitivity measurement. The transducers are assembled with air like backing medium (Rback in figure 1) with acoustic impedance Z = 425 Rayl and are stuck in Plexiglas structure. The modelling of the global measurement system is presented by figure 2. The transducers are based on behavioural temporal model of Redwood [7]. The nonlinear medium are represented by "non_linear_Medium" component and correspond to the model of a nonlinear acoustic layer.

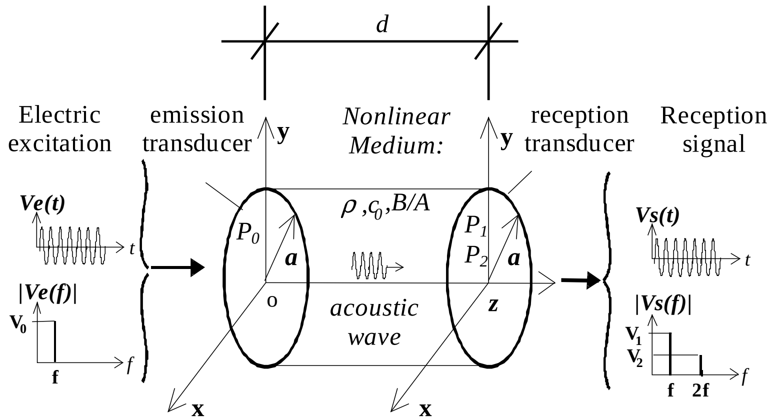

Figure1. Principle of measurement cell

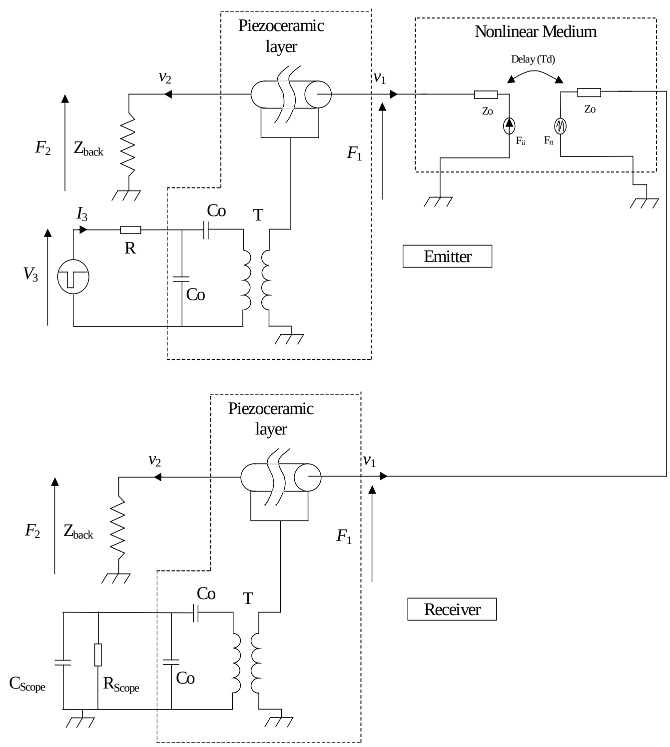

Figure 2. Modelling of the global ultrasound system measurement

1.2 Theoretical aspect of the non linear propagation

The propagation equation in nonlinear acoustic medium is based on the Burger formulation. This equation is true if we consider not attenuation and not diffraction. The plane wave propagation in a nondissipative medium (without losses) is described below:

$$\frac{\partial u}{\partial z}-\frac{\beta}{co^2}.u.\frac{\partial u}{\partial \tau}=0 \qquad (1)$$

With *co* the acoustic medium celerity, *u* is the particles velocity and $\tau = t - z/co$, *z* is the axis propagation. $\beta=1+0.5*B/A$ is the nonlinear parameter in liquid mediums. In the case of sinusoidal incident wave, the solution of the equation is given by:

$$u(z,t)=\sin\left(t-\frac{z}{co+\beta.u(z,t)}\right) \qquad (2)$$

The shock front appearance in the wave form is characterized by a coefficient noted σ ($0<\sigma<1$). So the relation (3) began:

$$u(z,t)=\sin\left(w.t-\frac{w.\sigma.l}{co+\beta.u(z,t)}\right) \qquad (3)$$

With $l = 1/(\beta*k*M)$, $k = w/co$ with w the pulsation of the wave in the beginning, $M = Uo/co$ is the Mach number, Uo is the amplitude of the ultrasonic source and $\sigma = \beta.w.Uo.z/co^2$ the shock formation coefficient.

1.3 Implementation of non linearities in a linear propagation line

Implementation of medium nonlinearity consists in modify the linear propagation line model which is based on the Branin model [8] presented Figure 3.

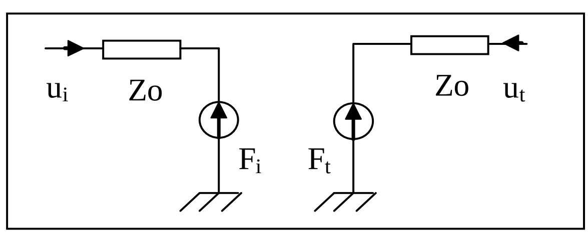

Figure 3. Equivalent electric diagram of the acoustic linear propagation in a medium

Notations i and t refer to the incident and the transmitted acoustic wave. *u* designate the velocity and *F* the force assimilated to pressure. *Zo* is medium characteristic impedance. The formulation (3) is included with a recurrent aspect in F_t which represents the acoustic wave retarded by the medium propagation time. A recurrent equation represents the formulation (3) which depends on the simulation temporal step in agreement with the parameter *dt*. *f* corresponds to the excitation frequency of the emitter transducer, *co* is the celerity specific to the medium and *Td* corresponds to the flight time of the acoustic wave. A starting condition is necessary to initialise the ultrasonic wave in order to avoid discontinuities problems in the acoustic wave form. The nonlinear acoustic medium model with VHDL-AMS language is :

```
ENTITY Nonlinearlayer IS
GENERIC  (Zo, Td, f, co, BsurA, sig, l, dt: REAL);
   PORT        (TERMINAL p1,m1,p2,m2  : Kinematic_v);
END Nonlinearlayer;
ARCHITECTURE simple OF Nonlinearlayer IS
terminal t11,t22,t7,t8,m7,m8 : Kinematic_v;
QUANTITY F1 ACROSS p1 TO m1;
QUANTITY F2 ACROSS p2 TO m2;
QUANTITY F11z ACROSS u1i THROUGH t11 TO m1;
QUANTITY F1z ACROSS u11i THROUGH t11 TO p1;
QUANTITY F2z ACROSS u22t THROUGH t22 TO p2;
QUANTITY F22z ACROSS u2t THROUGH t22 TO m2;
QUANTITY Fbelow across ubelow through t7 to m7;
QUANTITY F across u through t8 to m8;

BEGIN
if now < Dt USE
Fbelow == F;
F == sin(2.0*math_pi*f*dt - f*2.0*math_pi*sig*l/(co));
ELSE
Fbelow == F'DELAYED(dt);
F == sin(2.0*math_pi*f*now - f*2.0*math_pi*sig*l/(co*(1.0 +
(1.0+BsurA/2.0) * (Fbelow)/co)));
END USE;
if now < Td  USE
F22z ==   0.0;
F11z == - F1z;
F1z == u11i *Zo/2.0;
F2z == u22t *Zo/2.0;
ELSE
F22z == F'DELAYED(Td) - F2z;
F11z == F2'DELAYED(Td) - F1z;
F1z == (u11i + u22t'DELAYED(Td))*Zo/2.0;
F2z == (u22t + u11i'DELAYED(Td))*Zo/2.0;
End USE;
end simple;
```

1.4 B/A calculation with a comparative method

The reformulation of B/A parameter thanks to theoretical simulation is given by a comparative method [6]. This method requires to analyse the frequency spectrum of a medium taken as reference such as the water whose parameter B/A is supposed to be known, and to carry out following calculation:

$$\left(\frac{B}{A}\right)_x = \left(\frac{Vsr2_x}{Vs2_r}\right)\left(\frac{Vsr1_r}{Vsr1_x}\right)^2 \cdot \frac{\rho_r . c_r}{\rho_x . c_x} \cdot \frac{\rho_x . c_x^{\,3}}{\rho_r . c_r^{\,3}} \cdot \left(\left(\frac{B}{A}\right)_r - 2\right) - 2 \qquad (4)$$

Notations r and x referred to respectively the medium reference parameters and the analysed medium parameters. Vs1 and Vs2 are the fundamental amplitude and the second harmonic amplitude. ρ is the volumic density. c is the acoustic celerity. In this formulation, diffraction and attenuation effect are neglected.

2. SIMULATION RESULTS

The studied transducers are produced with PZT ceramic of P188 type (Quartz et silice®) with characteristics are recalled in table 1.

Table 1. Transducers acoustic characteristics

Parameters	Quantity	Value Type A	Value Type B
F_0	Frequency resonance (MHz)	2.25	4.5
A	Area (mm²)	132.73	132.73
e	Thickness (mm)	1	0.5
Zt	Acoustic impedance (Mrayls)	34.9	34.9
c_0	Acoustic velocity (m/s)	4530	4530
Co	Capacitor of the ceramic disc (pf)	1109.8	2910
E_{33}	Dielectric constant	650.0	650.0
kt	Thickness coupling factor	0.49	0.49
h_{33}	Piezoelectric Constant	$1.49\cdot10^9$	$1.49\cdot10^9$

The software used for VHDL-AMS simulation is ADMS v3.0.2.1 of Mentor Graphics company. The global measurement cell modelling implemented with VHDL-AMS writing of the figure 2 is simulated. The amplitude of the emitter transducer is fixed at 1Volt with a frequency of 2,25 MHz. The electric response issued to the receiver transducers is analyzed by a Fast Fourier transform with rectangular window for 10µs. Biological mediums analyzed in simulation are compared with the measurement cell results for liquid mediums like water, blood and milk. *B/A* parameter of human fat tissue and liver is considered well known in followings works [2,3]. Table 2 gives acoustic characteristics of simulated mediums.

Table 2. Medium biologic acoustic characteristics

Medium	Acoustic impedance MRayl	Acoustic speed m/s	B/A
Water	1.5	1509	5.0
Blood	1.678	1586	6.0
Human fat tissue	1.376	1445	10.9
Liver	7.6	1573	6.54
Milk	1.569	1531	5.9

Fundamental and second harmonic amplitude obtained with the fast Fourier transform as function to the biological mediums analyzed are presented in table 3.

These values are then used to estimate B/A parameter with the relation (4) and compared to B/A parameter obtained with in vitro measurements (table 2). Figure 4 shows results obtained.

Table 3 Amplitude of fundamentals and second harmonics with simulation in Volt

Medium	Fundamental amplitude at 2.25 MHz	Second Harmonic at 4.5 MHz
Water	0.579 V	0.5 V
Blood	0.569 V	0.499 V
Human fat tissue	0.545 V	0.787 V
Liver	0.572 V	0.528 V
Milk	0.578 V	0.536 V

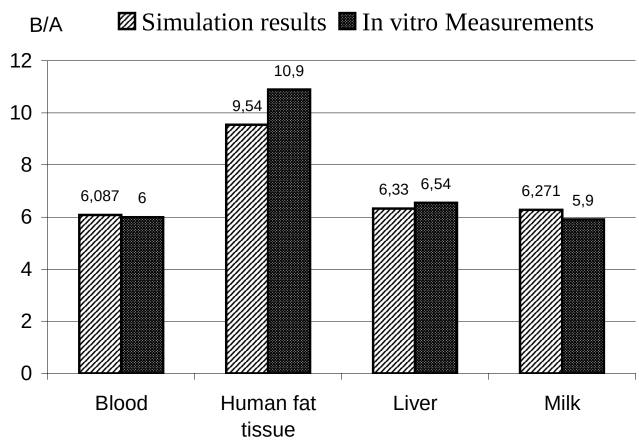

Figure 4. B/A parameter obtained in simulation compared to measurements value.

B/A estimation in simulation shows that we can characterize biological mediums with a sufficient precision between different mediums. For milk and blood we must also take into account the measurement of the acoustic celerity to differentiate the two mediums. For biological tissues like human fat and liver we obtain a great sensibility for the *B/A* estimation so we can easily predict the biological nature of the medium for this two cases. Maximum relative error is made with human fat tissue with an error of 12.5%.

3. CONCLUSION

The utilization of VHDL-AMS language shows the advantage to combine multiphysic discipline. Integration of nonlinear ultrasound aspect in simulation is also a new approach here. Usual medium modellings are based on transmission line theory and our medium model implements the nonlinear propagation phenomenon and permits us to analyze harmonic generation for a sinusoidal excitation case. Characterization of some biological mediums gives a serious opportunity to perform ultrasonic imaging system. *B/A* obtain in simulation is in good agreement with thermodynamic experimental results. *B/A* parameter used for simulate mediums have been obtain with a precision which depends of measurement methodology for example with blood we find a B/A of 6.0 with thermodynamic method [2] and 7.3 with finite amplitude method [3].

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