SPICE Modeling of Hybrid Multi-Frequency Ultrasound Transducer

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Abstract: - Whereas ultrasound application has been emerging, the need of reliable transducer to comply with that purpose is also aroused. Multi-resonance transducer using lead zirconate titanate piezoelectric ceramics (PZT) was designed several years ago for dual Doppler and B mode use. As polymer material being popular in medical ultrasound, there are chances to combine it with former piezoelectric material in designing diagnostic transducer to get hybrid characteristics required for multi-frequency application. In this work, SPICE model of ceramic-polymer piezoelectric has been described. Using Leach's approach, the modeled transducer covers triple peaks resonances. Electro-acoustic circuit simulation level shows that by hybridization, characteristics of both materials are providing a satisfying performance for multi-frequency transducer.

Key-Words: - Piezoelectric, Ceramic, Polymer, SPICE, Ultrasound, Transducer, Modeling

1 Introduction

Recently, ultrasound becomes prominent in several applications especially in medical field to improve the health services either for diagnostic or therapy purpose. Amongst cases, both B mode tomography and Doppler mode are widely used in clinical diagnostic. For each mode, medical experts are used to operating different ultrasonic probe: one for Doppler and the other for B mode [1]. The circumstance is less convenient so that the need of single transducer which covers multi-frequency becomes important. Moreover, wide-band and good impulse response are required in imaging applications [2].

PZT (lead zirconate titanate) piezoelectric ceramics, since the very beginning of transduction phenomena, have being used in device for transmitting and receiving ultrasonic. The reason is its superior ability to convert mechanical to electrical energy and vice versa (known as electromechanical coupling factor). In the meanwhile, polymer material such as polyvinylidene fluoride (PVDF) has come into use for implementing some ultrasonic probes. It has high electrical impedance for high frequency system but less sensitive. Using advantages and compensating each other disadvantages of both materials imposes a combination possibility in order to get hybrid characteristics such as acoustic impedance, bandwidth, and radiation patterns required for multi-frequency application.

A simulation of transducer's model is useful in order to verify the preliminary design. Hence, SPICE implementation of hybrid multi-frequency transducer has been developed in this paper.

2 Multi-Frequency Principle

An example of work in dual resonances ultrasonic probe for medical application was introduced in [1]. It focused on obtaining a high resolution B mode and a high sensitivity Doppler mode image with one ultrasonic probe instead of two different probes. 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. As a result, dual frequencies of 3.75 MHz and 7.5 MHz (dual peaks of the power spectrum) for diagnostic purpose had been accomplished.

The floating internal electrode structure as been shown in Fig.1 is reliable in case of lead connection. It is connected in series both acoustically and electrically.

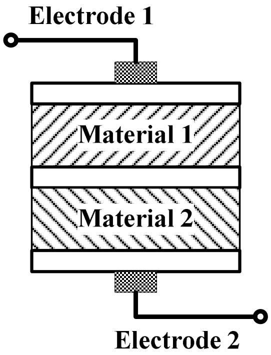

Fig. 1 Serial Configuration

A multi-frequency resonance mechanism as effect of thickness ratio variation of two homogeny ceramic materials with opposite poling directions was explained in detail on [1].

3 Electro-Acoustic Model

Nearly eight decades ago, the study about electricity analogy into another field (mechanics, heat, etc.) had been reviewed [3]. By discovery of relation between certain differential equations on vibrating mechanical bodies with electrical units, the point of view of the systems was broadened [4]. Some studies were brought by Rayleigh [5]. Those old concepts become a fundamental basis for similar works in related fields until nowadays.

On the other hand, progresses in electrical circuit elements and instrumentations have made the electrical systems very helpful and effective tool for most of system analysis. Since then, analogous electrical circuits to solve problems on mechanical, acoustical, and another has been increasing in practice. It has been recognized that the "voltage-force-pressure" analogy is the more advantageous with respect to acoustic device and electrostatic such as piezoelectric than the later "current-force-pressure" analogy. Table 1 shows the "voltage-pressure" analogy. Table 1 shows the "voltage-force-pressure" analogy [4].

Table 1 Voltage-Force-Pressure Analogy

Acoustical	**Mechanical**	**Electrical**
Sound Pressure (*p*)	Force (*F*)	Voltage (*V*)
Volume velocity (*U*)	Velocity (*v*)	Current (*I*)
Volume displacement (*V*)	Displacement (*D*)	Charge (*Q*)
Acoustic Resistance (R_A)	Mechanical Resistance (R_M)	Resistance (*R*)
Inertance (M_A)	Mass (*M*)	Inductance (*L*)
Acoustic Compliance (C_A)	Mechanical Compliance (C_M)	Capacitance (*C*)
Acoustic Impedance (Z_A)	Mechanical Impedance (Z_M)	Impedance (*Z*)

As advancement of transducer models, the controlled source model proposed by Leach [6] is used in this work for describing equivalent circuit of piezoelectric material. It is more agreeable when applied to circuit analysis program like SPICE than those of Mason (by Morris and Hutchens) [7], Redwood [8], and KLM [9] former models.

The mechanical part of transducer is modeled as an acoustical transmission line. Consequently with electro-acoustic analogy, the lossy electrical transmission line is modeled as a lump ladder circuit, as in Fig.2, where R is the series resistance, L the series inductance, C the shunt capacitance, and G the shunt conductance per unit length.

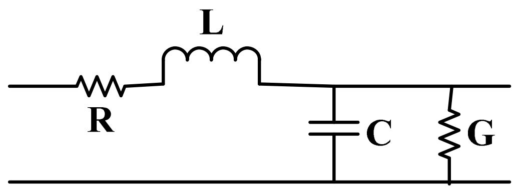

Fig. 2 Lump Ladder Circuit of Electrical Transmission Line

Derivation of transmission line's parameter is well-known which generates the following Equation (1) to (8):

$$R = 2\alpha Z_0 \quad (1)$$

$$L = A_Z \rho_{mo} \quad (2)$$

$$C = 1/(A_Z C^D) \quad (3)$$

$$G = 0 \quad (4)$$

$$Z_0 = \rho_{mo} v_a A_Z \quad (5)$$

$$v_a = \sqrt{C^D/\rho_{mo}} \quad (6)$$

$$\tan\delta_d = \frac{1}{\omega R_D C_0} \quad (7)$$

$$C_0 = \frac{\varepsilon A_Z}{l_z} \tag{8}$$

with α is the acoustic propagation loss, Z_0 the characteristic impedance (Ω), A_Z the piezoelectric area (m^2), ρ_{mo} the density (kg/m^3), C^D the relative elastic constant (N/m^2), v_a the sound velocity (m/s), δ_D the dielectric loss factor, C_0 the capacitance between electrodes (F), ε the permittivity (F/m) and l_z is the piezoelectric thickness (m) [2].

According to Leach [6], analogous circuit for the thickness-mode transducer is shown in Fig.3.

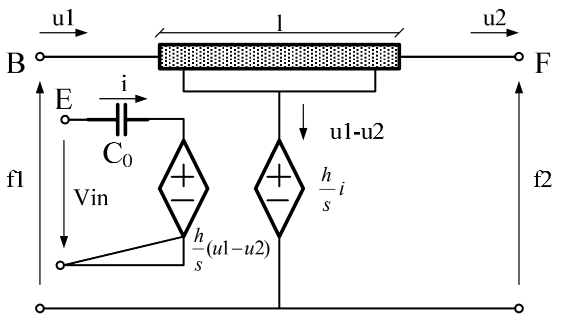

Fig. 3 Equivalent Model of Piezoelectric Element

Area along l (piezoelectric thickness) is a transmission line as in Fig.2. E, B and F are electrical port, mechanical back and front respectively. When piezoelectric constant (h) and other parameters are calculated, the model then can be simulated in circuit analysis program.

3.1 Piezoelectric Ceramic Parameter

According to data from [10] and [11], practical parameters of piezoceramic are varies.

As for Annon Piezo Technology Co., Ltd. PZT-5A product (ANN-P5AF2502) with thickness frequency 1 MHz, 2 mm thick and diameter 25 mm, the specification of piezoelectric ceramic element is shown in Table 2.

Table 2 Specification of Piezoceramic

	k_t	**k_p**	**d_{33}**	**C**	**α**
	0.43	0.66	420x10-12 C/N	2300 pF	-
PZT-5A	**ρ**	**Qm**	**tanδ**	**v_0**	**ε_{33}**
	7450 kg/m^3	100	0.023	4350 m/s	15.8 C/m^2
	$\epsilon^S x10^{-9}$	**$h_{33}x10^9$**			
	7.35 C^2/Nm^2	2.15			

3.2 Piezoelectric Polymer Parameter

Properties of PVDF film 110 µm uniaxially stretched poled with gold electrodes (PV110G) from Precision Acoustic Ltd are insufficient to be applied in simulation. Several publications [12], [13] have reported PVDF parameters as been compiled in Table 3.

Table 3 Specification of PVDF

	k_t	**k_p**	**d_{33}**	**C**	**α**
	0.127	-	30x10-12 C/N	31.81 pF	7.5
	ρ	**Qm**	**tanδ**	**v_0**	**ε_{33}**
PVDF	1750 kg/m^3	13	0.25	2250 m/s	5 C/m^2
	$\epsilon^S x10^{-12}$	**$h_{33}x10^9$**	**$c^D x10^9$**	**ε_r**	**Z**
	55.78 C^2/Nm^2	1.52 V/m	8.7	10	3.92 MRayl

3.3 Hybrid Model

Piezoelectric equivalent model in Fig.3 can be used for ceramic material as well as polymer material. When necessary, the circuit can be cascaded to make series connection both acoustically and electrically. In order to build hybrid model, two identical circuits as Fig.3 are combined. One uses PZT-5A parameters from Table 2 to be calculated by Equation (1) to (8) resulting values for equivalent model, while the other uses PVDF parameters from Table 3.

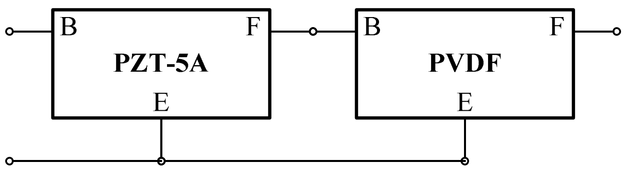

Fig. 4 Hybrid Transducer Model

Fig.4 shows series configuration of two material's equivalent models. Although in this work lossy characteristics (mechanical, dielectric, and electromechanical) of piezoelectric are considered [14], it must be taken to note that polymer material has complex additional losses than those of ceramic material [12] [13]. Certain polymer characteristic losses are neglected to simplify the preliminary design at this stage.

4 SPICE Implementation

SPICE is one of circuit analysis program that is reliable for many applications including in ultrasound systems [11]. Piezoelectric element model as in Fig.3 can be described in SPICE listing with Leach's [6] controlled source circuit.

```
.SUBCKT PZTR E B F
T1 B 1 F 1 LEN={lz} R={(2*PI*f*(Z0/Va))/Q}
+L={Z0/Va} G=0 C={1/(Z0*Va)}
V1 1 2 DC 6
E1 2 0 4 0 1
V2 E 3 DC 6
C0 3 0 {e*(Az/lz)}
F1 0 3 V1 {h*e*(Az/lz)}
F2 0 4 V2 {h}
R1 4 0 1000
C1 4 0 1
.ENDS
```

List above represents one single E-B-F block of Fig.4. Parameters assignment is based on Table 2 (for piezoceramic) and Table 3 (for polymer), while formula inside each bracket is linked to Equation (1) through (8).

When the model is being implemented into SPICE, it should be connected with signal source and medium model. Fig.5 shows example of complete circuit for simulation.

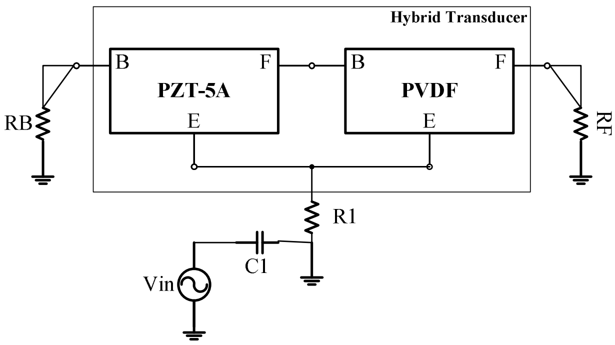

Fig. 5 Example Circuit for SPICE Simulation

5 Simulation Result

The proposed circuit was simulated firstly by WinSpice and consequently PSpice A/D. This section shows simulation results from PSpice A/D since it is more enhanced than WinSpice.

Fig. 6 shows frequency response of transducer. AC analysis was conducted to observe frequency behavior from 1 MHz to 10 MHz.

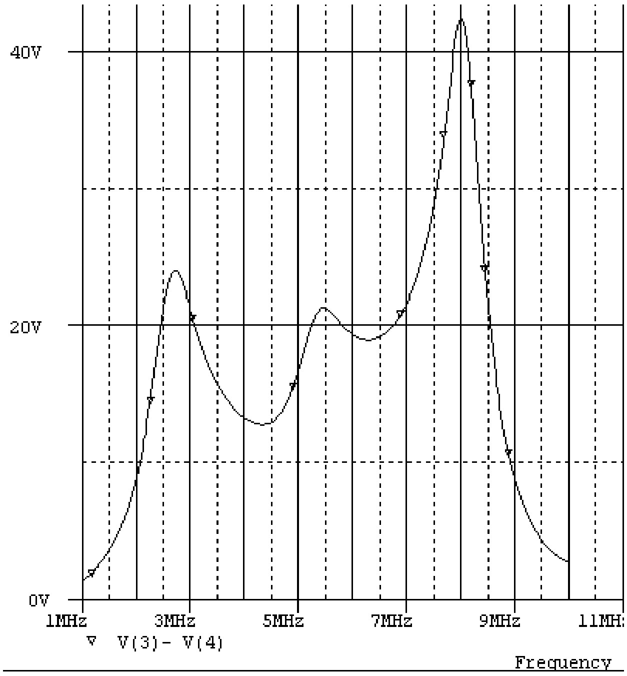

Fig. 6 Frequency Response of Transducer

There are three peaks of power spectrums: at 2.7035 MHz, 5.4716 MHz, and 8.0103 MHz. The last spectrum is higher than another, but for overall dB, bandwidth from 2.5 MHz to 8.5 MHz is considered flat.

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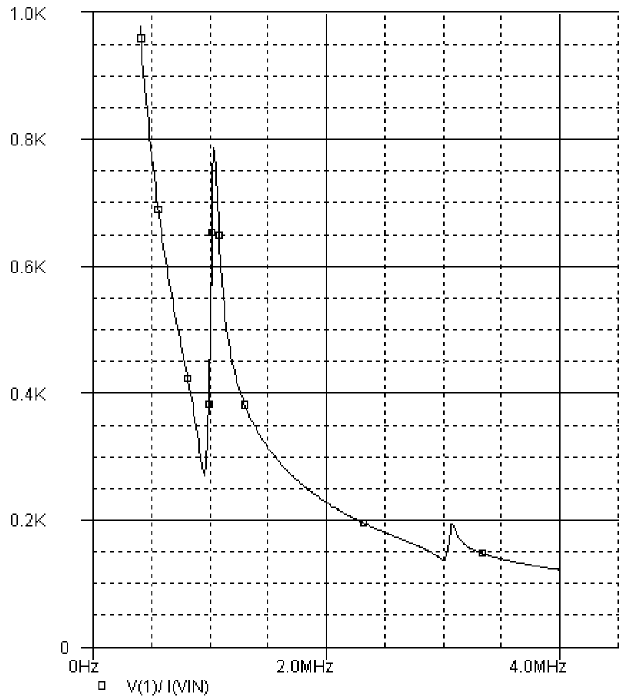

Fig. 7 Plot of Electrical Impedance Transducer

Electrical impedance of transducer was observed as in Fig.7. It gives turning point at about 1 MHz.

For transient behavior of transducer, simulation was set to pulse-echo mode in water medium. It conducted by adjusting front side parameter into water characteristics and ultrasound reflector.

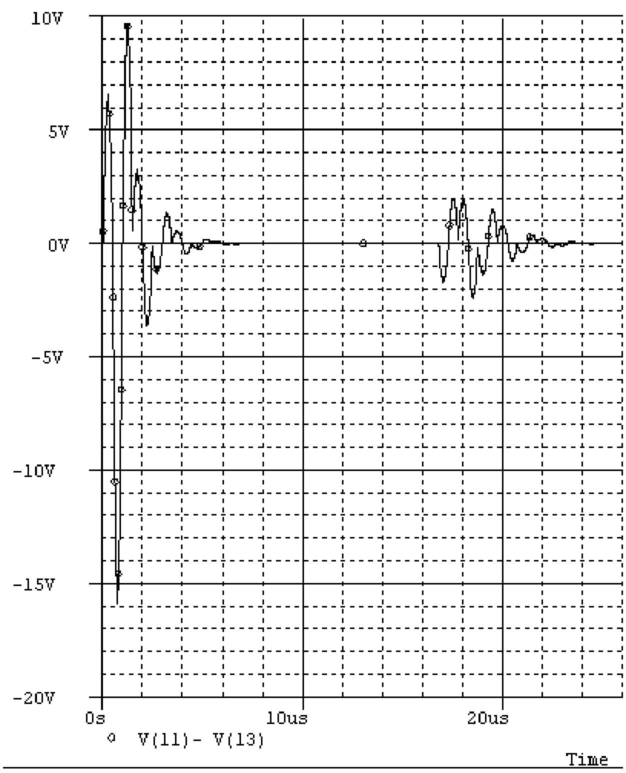

Fig. 8 Transducer Transient Simulation Graph

First wave is excitation period. Pulse repetition frequency to first echo is about 8 μs. Wave shape at Fig.8 shows various frequency components with amplitude around 4 Volt peak-to-peak.

6 Conclusion

SPICE 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.

Future work would be in detailed design which includes matching element, backing and loading consideration, also single or array configuration. Furthermore, the model could be improved so that it would be prepared for fabrication of hybrid multi-frequency ultrasound transducer.

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