Design of Hybrid Model of Ultrasonic Transducer

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ABSTRACT: *Newly, ultrasound becomes projecting in several applications especially in medical field to improve the health services either for diagnostic. The advent of ultrasound applications raises the need of reliable transducer to comply with that purpose. As polymer material being popular in medical ultrasound, there are chances to combine it with former piezoelectric ceramic 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. With signal conditioner circuit, complete analog system for ultrasound has also been developed. Initially transducer test for ceramic and polymer model were generated. By filtering and amplifying frequency range from 1 MHz until 10 MHz, the system bargains wideband medical ultrasonic acceptance. It gives smooth result of ultrasound signal for medical purposes.*

KEY WORDS: *Piezoelectric transducer, SPICE model, Hybrid transducer model*

Introduction

Ultrasonic sensing techniques have become mature and are extensively used in the numerous fields of engineering and basic science. Actually, many types of conventional ultrasonic instruments, devices and sophisticated software are commercialized and used for both industrial and medical applications. One of advantages of ultrasonic sensing is its outstanding capability to probe inside objectives nondestructively because ultrasound can propagate through any kinds of media including solids, liquids and gases except vacuum. In typical ultrasonic sensing the ultrasonic waves are travelling in a medium and often focused on evaluating objects so that a useful information on the interaction of ultrasonic energy with the objects are acquired as ultrasonic signals that are the waveforms variations with transit time. Such ultrasonic data provides the fundamental basis for describing the outputs of ultrasonic sensing and evaluating systems. In this work, SPICE model of ceramic-polymer piezoelectric has been described. With signal conditioner circuit, complete analog system for ultrasound has also been developed. Initially transducer test for ceramic and polymer model were generated. By filtering and amplifying frequency range from 1 MHz until 10 MHz, the system offers wideband medical ultrasonic acceptance. It gives smooth result of ultrasound signal for medical purposes.

Model of Piezoelectric transducer

The model developed for piezoelectric transducer is shown in fig.1. The block T_1 represents the transmission line. Independent sources V_1 and V_2 are zero value sources, which are used as ammeters in the circuit. F_1 and F_2 are dependent current sources. The value of F_1 is given by $F_1 = h\ C_0 \times I(V_1)$, where $I(V_1)$ is the current through V_1. The voltage across the dependent voltage source E_1 is given by $E_1 = V(4)$, where $V(4)$ is the voltage at node *4* i.e. the voltage across C_1. The dependent current source F_2 which charges C_1 is given by $F_2 = h \times I(V_2)$, where $I(V_2)$ is the current through V_2 and h is the ratio of the piezoelectric stress constant in the direction of propagation and the permittivity with constant strain . Resistor R_1 is included to prevent node 4 from being a floating node. From the mechanical side (i.e. transmission line T1), the difference between the velocity of each surface normal to the propagation path, represented by the currents u_1 and u_2 controls the current source F_1. The node labels E, B and F, respectively, denote the electrical, back, and front ports.

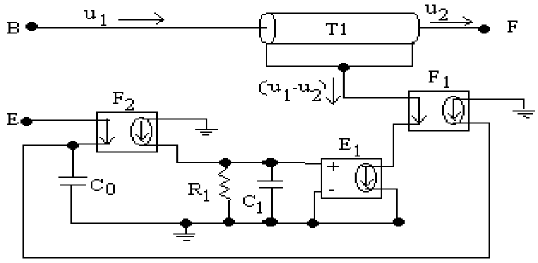

Fig. 1 Model of a piezoelectric transducer

MODEL OF PZT 5A- PVDF HYBRID TRANSDUCER

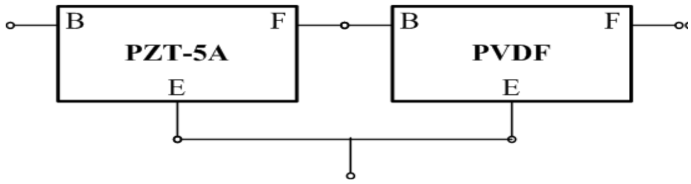

Fig. 2 : Hybrid Transducer Model

Fig. 2 shows series configuration of two material's equivalent models. Although in this model lossy characteristics (mechanical, dielectric, and electromechanical) of piezoelectric are considered, it must be taken to note that polymer material has complex additional losses than those of ceramic material.

The piezoelectric material PZT-5A and PVDF whose material data was obtained from [1], [2], [3], and [6] was chosen and given in table 1

TABLE 1. PHYSICAL PROPERTIES OF TRANSDUCERS AT 25 ^{O} C

S.No	Physical properties at 25^{0}C	PZT-5A	PVDF
1	Density (ρ) (kg/m^3)	7750 [3]	1780 [2]
2	Mechanical Q (Q_m)	75 [3]	19 [6]
3	Sound velocity (c) (m/s)	4350 [3]	2200 [2]
4	Permitivity with constant strain (ε^s) ($C^2/Nm^{2)}$	7.35×10^{-9} [3]	55.78×10^{-9} [6]
5	Piezoelectric stress constant (e^{33}) ($C/m^{2)}$	15.8 [3]	0.16 [6]
6	Acoustic Impedance (MRayl)	33.7 [3]	2.7 [2]
7	Piezoelectric Constant (10^{-12} C/N)	d_{33} = 374 [1] d_{15} = 584 [1]	d31=23 [6] d32=4 [6] d33=-33 [6]
8	Coupling factor (K_{33})	0.66 [3]	0.2 [6]

Assisted with the definition of the low loss characteristic impedances equation, following relationships can be obtained

$$L = A \cdot \rho \tag{1}$$

$$C = \frac{1}{A\rho c^2} \tag{2}$$

$$R = 2\rho c A \alpha_v \tag{3}$$

$$G = \frac{2\alpha_{tc}}{\rho c A} \tag{4}$$

Mechanically, a transmission line T of length *len* (m) represents the acoustical layer. The length is selected to achieve the desired center frequency *f* (Hz) of the transducer. With fixed ends, the piezoelectric plate has a fundamental resonant frequency as

$$f = \frac{c(T)}{2 \cdot len} \tag{5}$$

Where *c(T)* is the velocity of sound through it at temperature *T*.

Using equations (1), (2) and (3) the piezoelectric material density *ρ*, required for transmission line, *L* and *C* values can be calculated. The mechanical factor Q_m describes the shape of the resonance peak in the frequency domain. The relation between angular frequency *ω*, inductance *L* and the resistance *R* is given as [5]:

$$Q_m(T) = \frac{\omega L}{R} \tag{6}$$

In the electrical section, the static capacitance C_0 (T) at temperature T is calculated as

$$C_0(T) = \frac{\varepsilon^S(T) \cdot A}{len} \tag{7}$$

where ε^{s}(T) (C^2/Nm^2) is the permittivity with constant strain at temperature T [3]. The latter is related to the permittivity with constant stress (free) ε^T as :

$$\frac{\varepsilon^T(T)}{\varepsilon^S(T)} = \frac{1}{1-k^2(T)} \quad (8)$$

Where k (T) is the piezoelectric coupling constant at temperature T.

The mechanical and electrical sections interact with two current controlled sources. From the mechanical side, the deformation itself is not measurable, but the current representing the rate of deformation is the difference between the velocity of each surface normal to the propagation path, represented by the currents u_1 and u_2, is the rate of deformation. This current (u_1 - u_2) controls the current source F_1. It has a gain equal to the product of the transmitting constant h (N/C), and the capacitance C_0. h is the ratio of the piezoelectric stress constant e^{33} (C/m^2) in the direction of propagation and the permittivity with zero or constant strain ε^S. In the thickness mode it is [3].

$$h(T) = \frac{e^{33}(T)}{\varepsilon^S(T)} \quad (9)$$

This source's output is in parallel with the capacitor C_0(T). The result is a potential difference across the capacitor that is proportional to the deformation. In the electrical section, the current through the capacitor C_0(T) controls the current source F_2. The gain for this second current source is h(T). Its output needs to be integrated to obtain the total charge on the electrodes that proportionally deforms the transducer. The integration is performed by the capacitor C_1. The voltage controlled voltage source E_1 with unity gain is a one-way isolation for the integrator.

To evaluate the model, the model parameters of PZT-5A and PVDF transducers were calculated using equations (1, 2, 3, 5, 6, 7, 9) and given in table 2.

TABLE 2 MODEL PARAMETERS OF TRANSDUCERS

S.No.	Model parameters	PZT-5A	PVDF
	Physical parameters		
1	Diameter (mm)	12.7	12.5
2	Cross sectional area (A) (m^2)	0.0001267	0.0001227
3	Center frequency (MHz)	5MHz	5MHz
	Equivalent lossy transmission line parameters (Mechanical section)		
4	C	53.8nF	945.8nF
5	R	411kΩ	361.18 kΩ
6	L	981mH	218 mH
7	G	0	0
8	len	435µm	220 µm
	Electrical section parameter		
9	Static capacitance C_0	2.14nF	31.14nF
	Controlled sources parameter		
10	Transmitting constant (h) (N/C)	2.15×10^9	2.87×10^6
11	Current source gain (F_2)	2.15×10^9	2.87×10^6
12	Dependant current source gain (F_1)	4.60	0.09
13	Voltage control voltage source gain (E_1)	1	1
14	R_1	1 KΩ	1 KΩ
15	C_1	1F	1F

SIMULATION SETUP FOR ULTRASONIC SYSTEM

The analogous simulation schematic setup is described in figure 3, with the transducer sub circuit shown in figure 1. In this schematic an ultrasonic probe with acoustic matching layer is symbolized by the two three-port blocks X1 and X2, which involve established PSPICE piezoelectric model. The measuring cell is modeled using lossy transmission line.

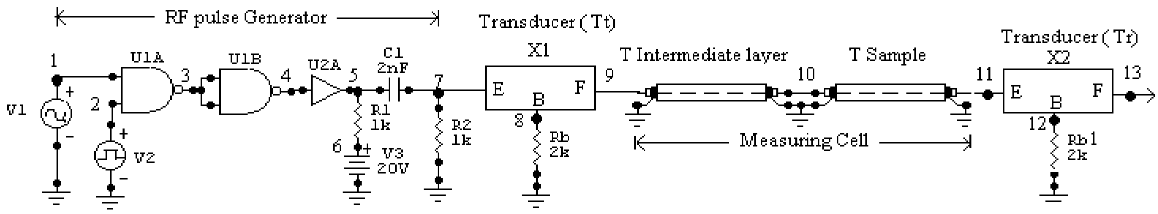

Fig.3 : **Simulation setup Schematic for ultrasonic test system.**

RESULT AND DISCUSSION

Transient analysis of the transducer model was done with the configuration shown in figure 4. An oscillation was observed after excitation of the piezoelectric crystal. The received signal was compared in the time domain. (Fig. 5, 6, 7)

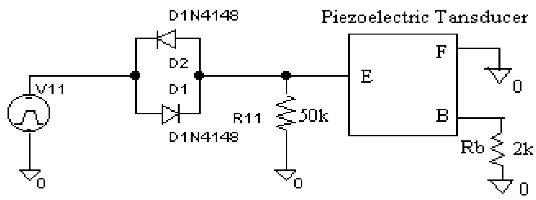

Fig. 4: Simulation setup for analysis of transient behavior of transducers.

Certain polymer characteristic losses are neglected to simplify the preliminary design at this stage. Fig. 6 shows the transient response of series configuration model.

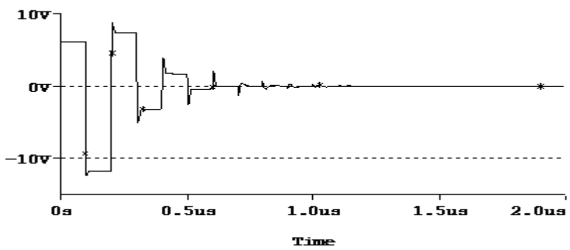

Fig 5 : Transient response of PZT-5A piezoelectric Transducer.

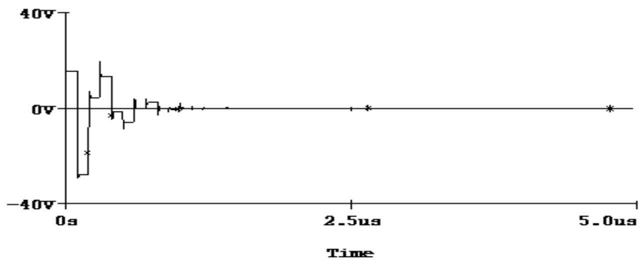

Fig 6: Transient response of PVDF Transducer

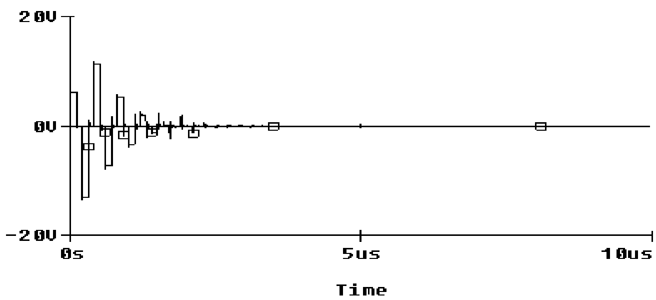

Fig. 7: Transient response of ceramic-polymer piezoelectric transducer (PZT-5A+PVDF) for multi-frequency ultrasonic system

Fig. 8 shows frequency response of transducer. AC analysis was conducted to observe frequency behavior from 1 MHz to 10 MHz. There are three peaks of power spectrums: at 2.8 MHz, 5.5 MHz, and 8 MHz. The last spectrum is higher than another, but for overall dB, bandwidth from 2.5 MHz to 8.5 MHz is considered flat.

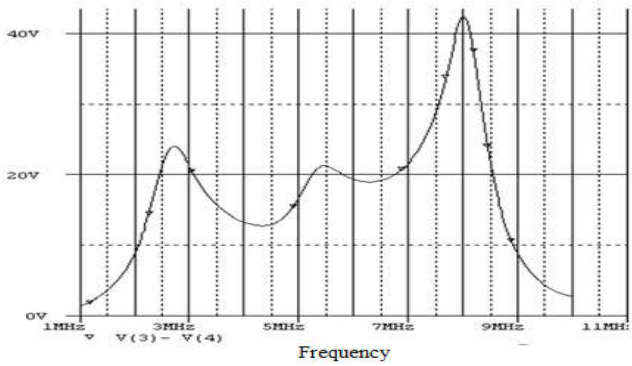

Fig. 8: Frequency response of Transducer

Electrical impedance of transducer was observed as in Fig.9. It gives turning point at about 1 MHz.

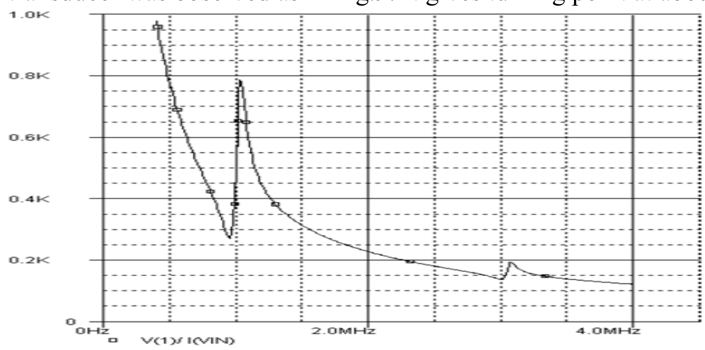

Fig. 9: Electrical Impedance of Transducer

Experimental validation for water sample is shown in fig. 10

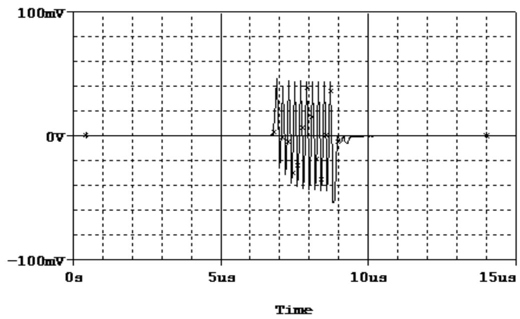

Fig. 10: Complete transient received by 5MHz ceramic-polymer piezoelectric transducer (PZT-5A+PVDF) for multi-frequency ultrasonic system at 25ºC in distilled water at d= 1 cm.

CONCLUSION

A 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.

REFERENCES:

[1] Berlincourt D., Krueger H.A., and Near C. Important Properties of Morgan Electroceramics, Morgan Electroceramics, Technical Pub., 2001, TP-226.

[2] Brown LF. IEEE Trans Ultrason Ferroelect Freq Contr. 2000;47:1377

[3] Kino G.S., Acoustic Waves: Devices, Imaging, and Analog Signal Processing. Englewood cliffs, N.J: Prentice-Hall, 1988. 601.

[4] Mattiat O. E. ,Ultrasonic Transducer Materials, Plenum Press, London, New York, 1971. 102-105.

*[5] Puttmer A., Hauptmann P., Lucklum R., Krause O. and Henning B., IEEE Trans. Ultrason., Ferroelect., Freq. Contr., **44**, 1997, 60-66.*

***[6]** Webster John G., Mechanical Variables Measurement - Solid, Fluid, and Thermal, CRC Press, 1999,Page 7-49.*