Analog SPICE Implementation of Multi-Frequency Ultrasound System

Imamul Muttakin, Nik Muhamad Arif, Syed Mohd Nooh, and Eko Supriyanto

***Abstract*—The emergence 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. 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. With signal conditioner circuit, complete analog system for ultrasound has also been developed. As initial, 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. With -5 to +5 voltage head-room, it gives smooth result of ultrasound signal for medical purposes.**

***Index Terms*—Piezoelectric, PZT, PVDF, SPICE, Ultrasound, Analog**

I. 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.

On the other hand, analog systems have been engaged with important responsibility in bordering digital systems to the real world in applications for instance analog signal processing and conditioning in biomedical measurements [3]. Sensor modeling into circuit behavior makes transducing problem become more compact for electrical analysis. The characteristics of device can be referred in term of electrical characteristics which is very useful in development stage of the system. Hence, an accurate equivalent circuit is a prerequisite for accurate sensor development. Furthermore, when transducer system is described in electronics, the help of Computer Aided Design (CAD) tools as well as Electronic Design Automation are great advantages in order to digitally simulate system's behavior comparing to conventional technology.

Simulation Program with Integrated Circuit Emphasis (SPICE), developed at Electronics Research Laboratory of the University of California Berkeley by Larry Nagel, is fashionable analog circuit simulator [4]. Orcad PSPICE is one of programs for solving electronics engineering's problem [5]. Its macromodel method is trusted for modeling various kind of circuits [6].

Furthermore, SPICE is consistently used for piezoelectric transducer equivalent circuit analysis since the work has been introduced in 1986 by Morris and Hutchens [7] [8]. Its sequel such PSPICE also been employed in simulating ultrasound system as in [9]. Even another work [10] specially extended an auxiliary tool named Circuit Modeling of Transducer (CMT) to automatically generate the SPICE file for transducer's equivalent circuit.

A simulation of system is useful in order to verify the preliminary design [11]. Thus, SPICE implementation of hybrid multi-frequency transducer has been developed in this paper. Analog model of ultrasound system has also been described.

II. ELECTRO-ACOUSTIC MODEL

Nearly eight decades ago, the study about electricity analogy into another field (mechanics, heat, etc.) had been reviewed [12]. By discovery of relation between certain differential equations on vibrating mechanical bodies with electrical units,

Manuscript received November 3, 2011. This work was supported by the Ministry of Higher Education (MOHE), Malaysia under Fundamental Research Grant Scheme (FRGS) vot 78696.

Imamul Muttakin is with Faculty of Health Science and Biomedical Engineering, Universiti Teknologi Malaysia (e-mail: muttakin.imamul@gmail.com; homepage: http://diagnostics.my/imamul/)

Nik Muhamad Arif is with Faculty of Health Science and Biomedical Engineering, Universiti Teknologi Malaysia (e-mail: nix_arif@yahoo.com)

Syed Mohd Nooh is with the Department of Clinical Science and Engineering, Faculty of Health Science and Biomedical Engineering, Universiti Teknologi Malaysia (e-mail: syedmohdnooh@utm.my)

Eko Supriyanto is with the Department of Clinical Science and Engineering, Faculty of Health Science and Biomedical Engineering, Universiti Teknologi Malaysia, UTM Skudai, 81310 Johor, Malaysia (phone: +60-755-35273; fax: +60-755-36222; e-mail: eko@biomedical.utm.my)

the point of view of the systems was broadened [13]. Some studies were brought by Rayleigh [14]. 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 I shows the "voltage-force-pressure" analogy [13].

As advancement of transducer models, the controlled source model proposed by Leach [15] [16] 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 [17], Redwood [18], and Krimholtz-Leedom-Matthaei (KLM) [19] [20] former models. While Mason's model (1942) became the root with lumped equivalent circuit, Redwood (1961) applied transmission line into the model perfecting mathematical transient response of piezoelectric. Then KLM circuit (1970) came up consisting frequency-dependent transformer network which make cascading device is possible. After all, Leach (1994) removed Mason's negative capacitor and KLM's transformer. A lossy transmission line was attached to consider acoustical attenuation [21].

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. 1, where R is the series resistance, L the series inductance, C the shunt capacitance, and G the shunt conductance per unit length.

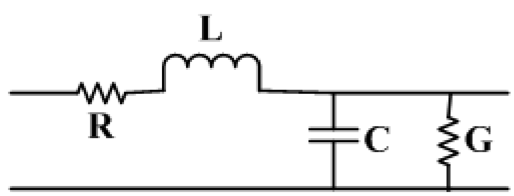

Figure 1. Lump Ladder Circuit of Electrical Transmission Line

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

$$R = 2\alpha Z_0 \tag{1}$$

$$L = A_z \rho_{mo} \tag{2}$$

$$C = 1/\left(A_z C^D\right) \tag{3}$$

$$G = 0 \tag{4}$$

$$Z_0 = \rho_{mo} v_a A_z \tag{5}$$

$$v_a = \sqrt{C^D/\rho_{mo}} \tag{6}$$

$$\tan\delta_d = \frac{1}{\omega R_D C_o} \tag{7}$$

$$C_o = \frac{\varepsilon A_Z}{l_Z} \tag{8}$$

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 [15], analogous circuit for the thickness-mode transducer is shown in Fig. 2.

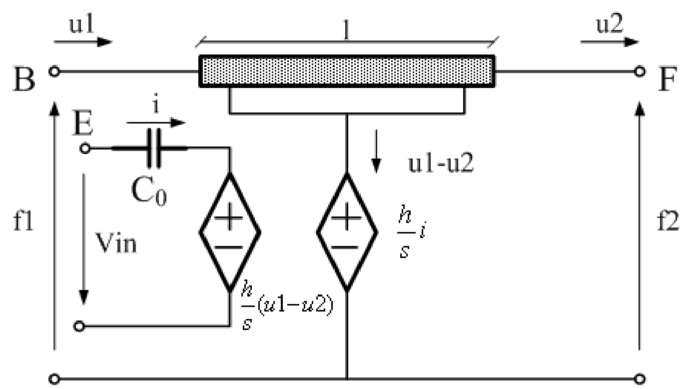

Figure 2. Equivalent Model of Piezoelectric Element

Area along l (piezoelectric thickness) is a transmission line as in Fig. 1. 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.

A. Piezoelectric Ceramic Parameter

According to data from [22] and [9], 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 II.

B. 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 [23], [24] have reported PVDF parameters as been compiled in Table III.

Table I
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)

Table II
SPECIFICATION OF PIEZOCERAMIC PZT-5A

k_t	d_{33} x 10^{-12}	C	ρ	Q_m	tanδ	v_0	ε_{33}	ϵ^S x 10^{-9}	h_{33} x 10^9
0.43	420 C/N	2300 pF	7450 kg/m^3	100	0.023	4350 m/s	15.8 C/m^2	7.35 C^2/Nm^2	2.15 V/m

Table III
SPECIFICATION OF PVDF

k_t	d_{33} x 10^{-12}	C	ρ	Q_m	tanδ	v_0	ε_{33}	ϵ^S x 10^{-9}	h_{33} x 10^9
0.127	30 C/N	31.81 pF	1750 kg/m^3	13	0.25	2250 m/s	5 C/m^2	55.78 C^2/Nm^2	1.52 V/m

III. MULTI-FREQUENCY METHOD

A. Multi-Resonance 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. 3 is reliable in case of lead connection. It is connected in series both acoustically and electrically.

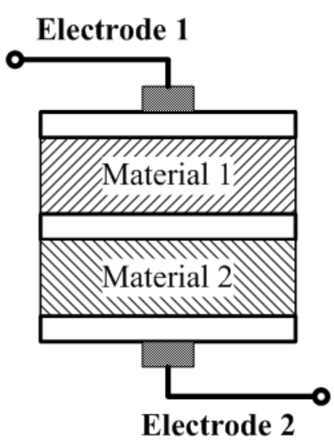

Figure 3. Serial Configuration

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].

B. Hybrid Model

Piezoelectric equivalent model in Fig. 2 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. 2 are combined. One uses PZT-5A parameters from Table II to be calculated by Equation (1) to (8) resulting values for equivalent model, while the other uses PVDF parameters from Table III.

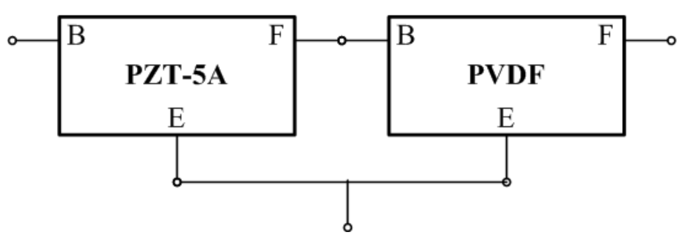

Figure 4. Hybrid Transducer Model

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 [21], it must be taken to note that polymer material has complex additional losses than those of ceramic material [23] [24]. Certain polymer characteristic losses are neglected to simplify the preliminary design at this stage.

IV. ANALOG CIRCUIT DESIGN

A. Transducer Equivalent Circuit

Equivalent model of piezoelectric element sketch in Fig. 2 is translated into circuit schematic as shown in Fig. 5.

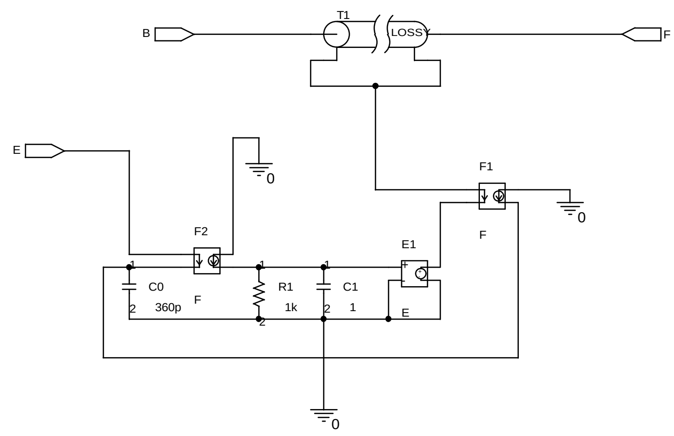

Figure 5. Transducer Model Circuit Schematic

From the figure, T1 represent a lossy transmission line embedding lump-ladder circuit with sensor parameters. E_1 is voltage-controlled voltage source (VCVS) while F_1 and F_2 are current-controlled current source (CCCS). The rest passive components C_0, C_1, and R_1 are derived from material and environment characteristics.

B. Band-Pass Filter

The first interface between transducer and analog system is a filter. It is required for rejecting frequency out of interests and also cancelling noise from external surrounding or internal circuit. To prevent undesired rough attenuation, active filter was proposed. The current-feedback operational amplifier (CFOA) or –current-feedback amplifier (CFA)– is used for gain component. It is suitable for high performance of analog signal processing and can be found commercially to employ filters, amplifiers, oscillators, etc. It also has additional advantage of providing a low impedance output voltage. This makes easy the cascading of similar filter sections to achieve higher-order filters. The good performances of the filter can be emphasised by SPICE simulation [25].

Sallen-Key topology was chosen for wideband bandpass filter. There are many famous implementation of this topology. For example, lowpass Sallen-Key filter providing Butterworth response with wide bandwidth (megahertz order) is useful for video-reconstruction filtering in HDTV applications. as well as before the Analog-to-Digital Converter (ADC) for anti-aliasing [26].

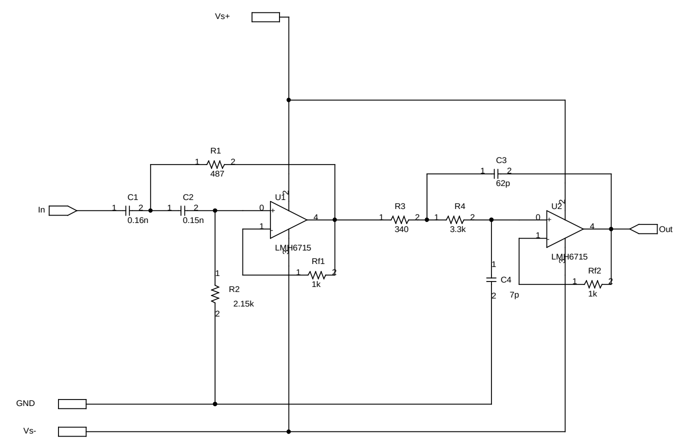

Figure 6. Filter Circuit

Figure 6 shows cascaded highpass filter and lowpass filter resulting wideband bandpass filter. The main component is LMH6715 operational amplifier from National Semiconductor. Instead of manually calculating the filter's parameters with complex mathematical formula, the manufacturer provides online tools for designing filter based on their products. By the help of Webench, all components value are obtained. It is designed for low-frequency cut-off 1 MHz and high-frequency cut-off 10 MHz to satisfy medical ultrasound frequencies.

C. Differential Amplifier

As in filter design, amplifier performances can be proven through PSPICE which is accordance with theoretical anticipations [27]. Again, CFA was used with differential topology in order to reject noise, common mode disturbance, and as it might be high frequency interferences. The circuit is shown in Fig. 7.

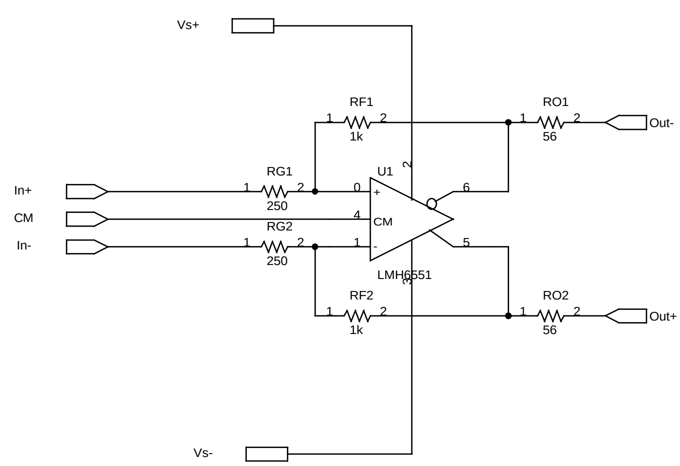

Figure 7. Amplifier Circuit

Gain part is LMH6551 differential high-speed operational amplifier from National Semiconductor. According the application note [28], amplification can be set by simply adjusting ratio of feedback resistor (R_F) and series resistor (R_G). Output resistor, capacitor, and voltage were prepared to be matched for interfacing with ADC in further data acquisition stage.

V. SPICE IMPLEMENTATION

As been introduced, SPICE is one of circuit analysis program that is reliable for many applications including in ultrasound systems. WinSpice is one of SPICE-based software which has no schematic editor yet powerful for scripting circuit list. For other version, PSpice is widely used for schematic design.

A. Multi-Frequency Transducer

Piezoelectric element model as in Fig. 2 can be described in SPICE listing with Leach's [15] 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 II (for piezoceramic) and Table III (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. 8 shows example of complete circuit for simulation.

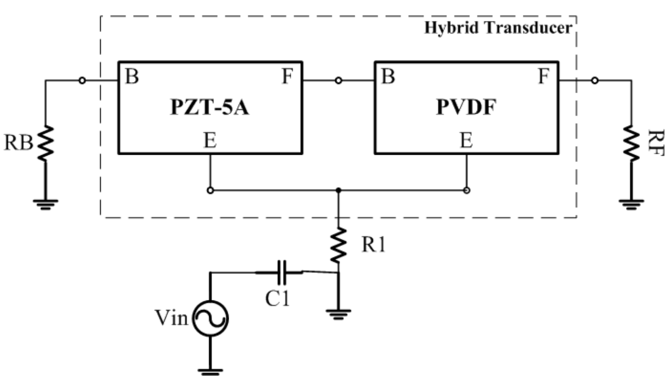

Figure 8. Example Circuit for SPICE Simulation

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

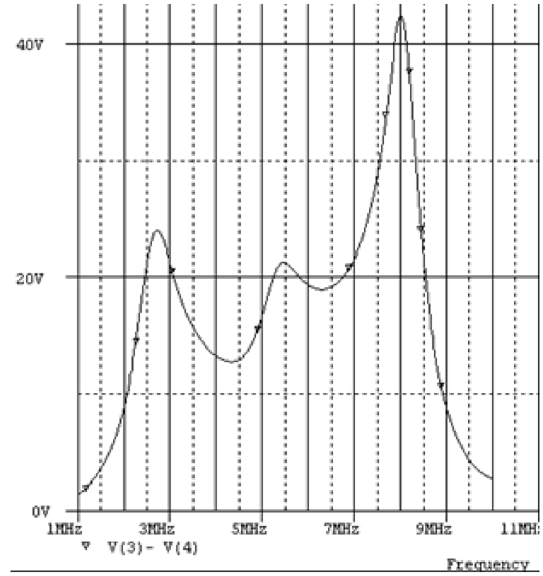

Figure 9. Frequency Response of Transducer

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.

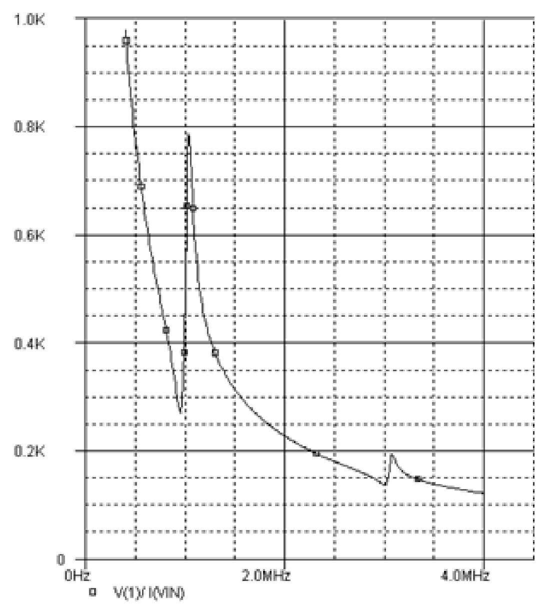

Figure 10. Plot of Transducer's Electrical Impedance

Electrical impedance of transducer was observed as in Fig. 10. 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.

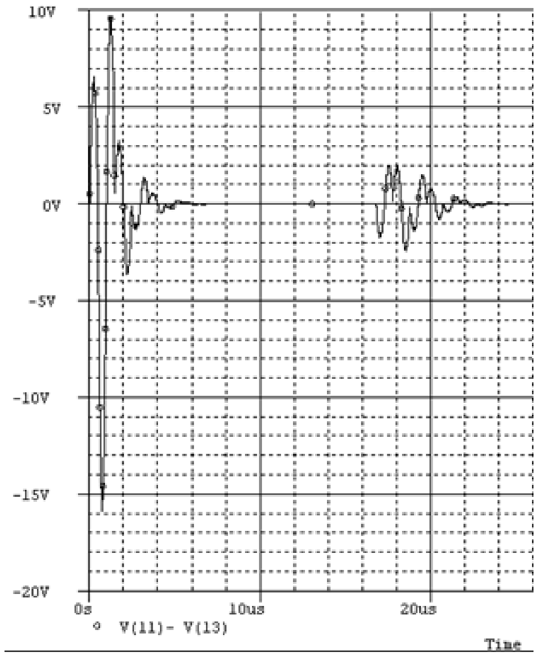

Figure 11. Transducer Transient Simulation Graph

First wave is excitation period. Pulse repetition frequency to first echo is about 8 µs. Wave shape at Fig. 11 shows various frequency components with amplitude around 4 Volt peak-to-peak.

B. Ultrasound System

This part will explain analog system test for ultrasound circuit and signal. For convenient in analysing the following stages, working frequency was chosen to be 1 MHz. Comparation between PZT and PVDF for 1 MHz system-generated ultrasound signal can be seen in Fig. 12. Output level difference between two materials is clearly occured for each characteristics. Signal shapes are also not similar. But both of which give exact frequency (1 MHz) with time delay about 5 μs for PZT and approximately 10 μs for PVDF.

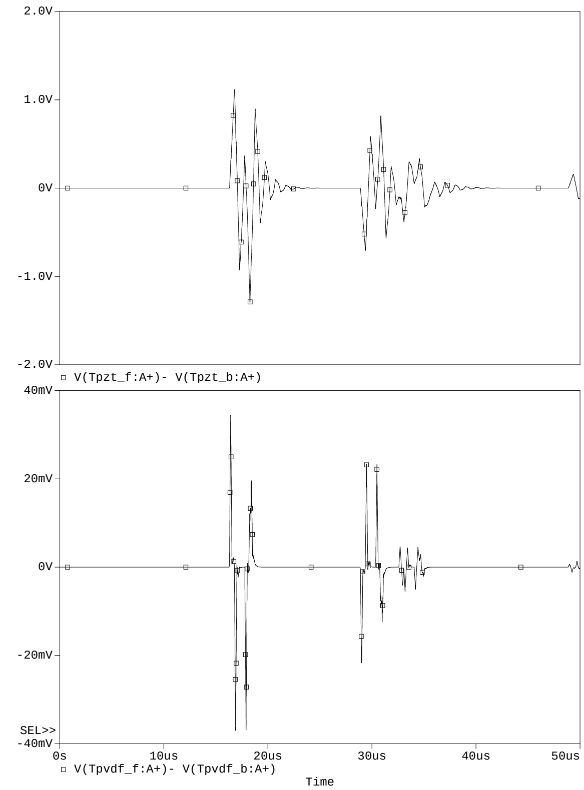

Figure 12. PZT and PVDF Signal

As been discussed at section III whereas polymer model neglected certain complex losses in modeling, it seems reasonable that PZT signal was steadily generated. So, PZT signal was taken into account.

Figure 13 shows analog system layout. It contains all block defined at previous section including sensor, filter, and amplifier. Signal source was single 10 V pulse to trigger the sensor. It is adjacent to series resistance and protecting diodes to guarantee the stability. Damp resistor was used for detecting echo signal. Additional transmission layers were placed to model the medium (in this case is water). Two identical bandpass filter was put to receieve signal from front layer and back layer of the sensor. Then after filtering, both signals were inputted differentially to the gain stage for amplification and adjustment. At the edge, there were capacitor and resistor load placed for matching purposes into the expected next implementation (ADC or transmission line).

As shown in Fig. 14, the analog system has -6 dB bandwidth about 9 MHz with first and second cut-off at 1 MHz and 10 MHz respectively. The attenuation is approximately 20dB at 300 kHz, and 20dB at 30 MHz.

Figure 15 shows signals at each node. On top is triggering source pulse. Ultrasound signal at front-back layer is shown in second graph from top. Filtering and amplification result were plotted in the last two graphs. The spectrums at Fig. 16 proved ultrasound frequency and signal-conditioning process. At first it has low-frequency components which was rejected simultaneously outputting a steady 1 MHz ultrasound signal.

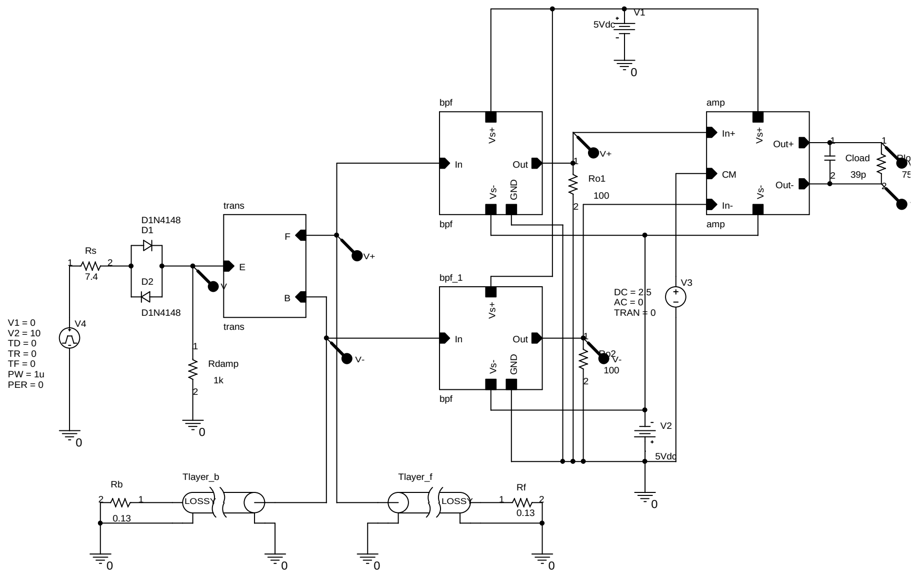

Figure 13.   Analog System Layout

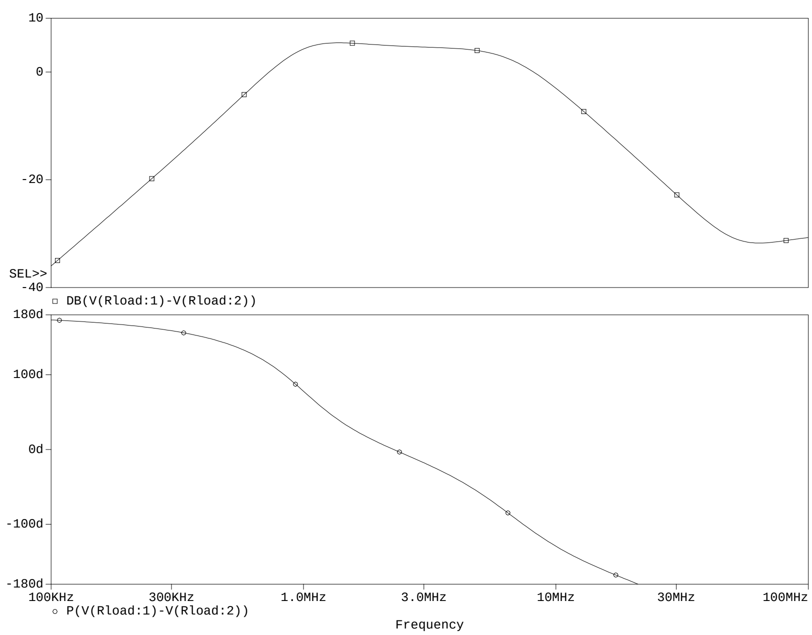

Figure 14.   Frequency Response of Analog Circuit

VI. Conclusions

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.

Analog ultrasound system model is established. The frame can be extended to digital circuits part to completely model ultrasound instrument's behavior. Also with this work, the purpose of medical ultrasound system is supported by analog SPICE modeling. As for example transmission line model of biological tissue has been studied, there are chances to implement similar work in research and development stage.

Acknowlegment

The authors would like to express our thankfulness to Universiti Teknologi Malaysia (UTM) and Ministry of High Education (MOHE), Malaysia for supporting and funding this

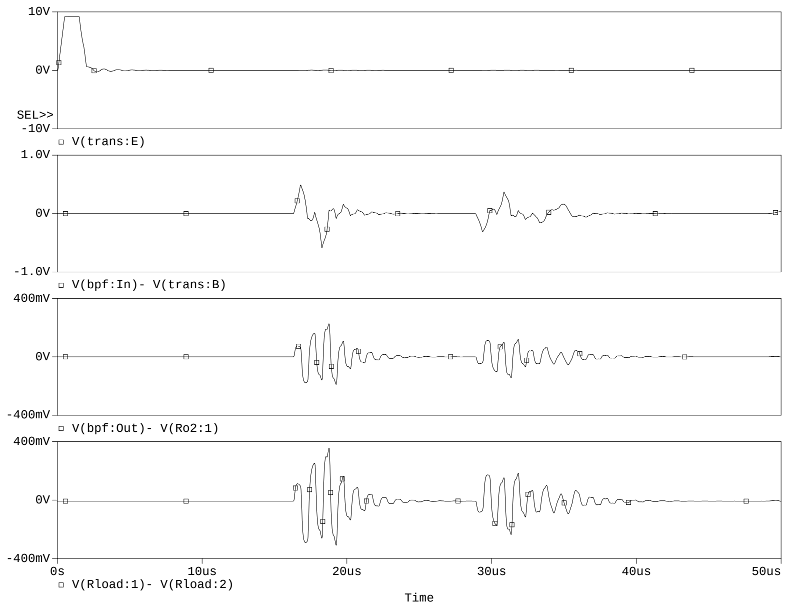

Figure 15. Ultrasound Signal

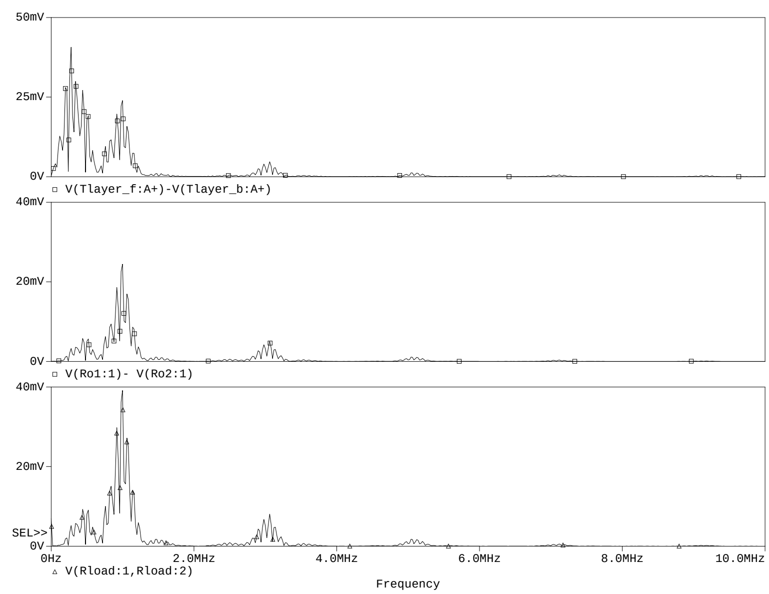

Figure 16. FFT Ultrasound Signal

study under vot 78696. Our appreciation goes to the Diagnostics Research Group (Biotechnology Research Alliance) members for their ideas and comments on this paper, also to everyone who has contributions in this work.

REFERENCES

[1] S. Saitoh, M. Izumi, and Y. Mine, "A dual frequency ultrasonic probe for medical applications," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 42, no. 2, pp. 294–300, March 1995.

[2] Y. C. Chen, "Acoustical transmission line model for ultrasonic transducer for wide-bandwidth application," *Acta Mechanica Solida Sinica*, vol. 23, no. 2, pp. 124–134, April 2010.

[3] A. H. A. Madian, S. A. B. Mahmoud, and A. M. C. Soliman, "Configurable analog block based on cfoa and its application," *WSEAS Transactions on Electronics*, vol. 5, no. 6, pp. 220–225, 2008, cited By (since 1996) 1.

[4] P. W. Tuinenga, *SPICE: A Guide to Circuit Analysis Simulation and Analysis Using PSpice*, 3rd ed. NJ: Prentice-Hall, 1988.

[5] D. Biolek, J. Kadlec, V. BiolkovÃą, and Z. Kolka, "Interactive command language for orcad pspice via simulation manager and its utilization for special simulations in electrical engineering," *WSEAS Transactions on Electronics*, vol. 5, no. 5, pp. 186–195, 2008, cited By (since 1996) 0.

[6] D. A. Biolek, V. B. Biolkova, and Z. B. Kolka, "Pspice modeling of buck converter by means of gtfs," *WSEAS Transactions on Electronics*, vol. 3, no. 2, pp. 93–96, 2006, cited By (since 1996) 2.

[7] S. A. Morris and C. G. Hutchens, "Implementation of masonŠs model

on circuit analysis programs," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. UFFC-33, no. 3, pp. 295–298, May 1986.
[8] J.-M. Galliere, P. Papet, and L. Latorre, "A unified electrical spice model for piezoelectric transducers," in *Behavioral Modeling and Simulation Workshop, 2007. BMAS 2007. IEEE International*, sept. 2007, pp. 138 –142.
[9] J. V. Deventer, T. Lofqvist, and J. Delsing, "Pspice simulation of ultrasonic systems," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 47, no. 4, pp. 1014–1024, July 2000.
[10] J. Liu, T. Watanabe, N. Kijima, M. Haruta, Y. Murayama, and S. Omata, "Cmt: An equivalent circuit modeling tool for ultrasonic transducer," in *Sensor Technologies and Applications, 2008. SENSORCOMM '08. Second International Conference on*, aug. 2008, pp. 592 –597.
[11] I. Muttakin, S.-Y. Yeap, M. M. Mansor, M. H. M. Fathil, I. Ibrahim, I. Ariffin, C. Omar, and E. Supriyanto, "Low cost design of precision medical ultrasound power measurement system," *International Journal of Circuits, Systems and Signal Processing. NAUN Press.*, vol. 5, no. 6, pp. 672–682, October 2011. [Online]. Available: http://www.naun.org/journals/circuitssystemssignal/17-345.pdf
[12] F. A. Firestone, "A new analogy between mechanical and electrical systems," *Jour. Acoust. Soc. Amer.*, vol. 4, pp. 239–267, 1933.
[13] B. B. Bauer, "Equivalent circuit analysis of mechano-acoustic structures," *Trans. IRE*, vol. AU-2, pp. 112–120, July-Aug 1954.
[14] L. Rayleigh, *The Theory of Sound*. N. Y.: Dover Publications, 1945, vol. 1.
[15] W. M. Leach, "Controlled-source analogous circuits and spice models for piezoelectric transducers," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 41, no. 1, pp. 60–66, January 1994.
[16] W. M. Leach, Jr., "Computer-aided electroacoustic design with spice," *J. Audio Eng. Soc*, vol. 39, no. 7/8, pp. 551–563, July/Aug 1991.
[17] W. Mason, *Electromechanical transducers and wave filters*, ser. Bell Telephone Laboratories series. D. Van Nostrand Co., 1948.
[18] M. Redwood, "Transient performance of a piezoelectric transducer," *Jour. Acoust. Soc. Amer.*, vol. 33, no. 4, pp. 527–536, April 1961.
[19] R. Krimholtz, D. A. Leedom, and G. L. Matthaei, "New equivalent circuit for elementary piezoelectric transducers," *Electron Letters*, vol. 6, no. 13, pp. 398–399, June 1970.
[20] D. Leedom, R. Krimholtz, and G. Matthaei, "Equivalent circuits for transducers having arbitrary even- or odd-symmetry piezoelectric excitation," *Sonics and Ultrasonics, IEEE Transactions on*, vol. 18, no. 3, pp. 128 – 141, jul 1971.
[21] A. Puttmer, P. Hauptmann, R. Lucklum, O. Krause, and B. Henning, "Spice model for lossy piezoceramic transducer," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 44, no. 1, pp. 60–66, January 1997.
[22] J. H. Goll, "The design of broad-band fluid-loaded ultrasonic transducers," *IEEE Transactions on Sonics and Ultrasonics*, vol. SU-26, no. 6, pp. 385–393, November 1979.
[23] L. F. Brown, "Design considerations for piezoelectric polymer ultrasound transducers," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 47, no. 6, pp. 1377–1396, November 2000.
[24] R. S. Dahiya, M. Valle, and L. Lorenzelli, "Spice model for lossy piezoelectric polymer," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 56, no. 2, pp. 387–395, February 2009.
[25] M. T. Abuelma'atti and S. M. Al-Shahrani, "A new polyphase mixed-mode bandpass filter section using current-feedback operational amplifiers," *WSEAS Transactions on Electronics*, vol. 2, no. 4, pp. 128–131, 2005, cited By (since 1996) 2.
[26] Z. Erdeiz, L. A. Dicso, L. Neamt, and O. Chiver, "Symbolic equation for linear analog electrical circuits using matlab," *WSEAS Transactions on Circuits and Systems*, vol. 9, no. 7, pp. 493–502, 2010, cited By (since 1996) 0.
[27] M. Siripruchyanun, C. Chanapromma, P. Silapan, and W. Jaikla, "Bicmos current-controlled current feedback amplifier (cc-cfa) and its applications," *WSEAS Transactions on Electronics*, vol. 5, no. 6, pp. 203–219, 2008, cited By (since 1996) 13.
[28] NationalSemiconductor, "Lmh6551 differential, high speed op amp," February 2005.

Imamul Muttakin is a graduate research assistant in Diagnostics Research Group at Universiti Teknologi Malaysia. He obtained his Bachelor Degree in Electronics Engineering from Institut Teknologi Bandung (Indonesia) in 2009. His research is in the areas of digital electronics and (currently) in system application on ultrasound exposimetry. He is affiliated with IEEE as student member. In TELKOMNIKA Journal, he has served as invited reviewer. Besides, he is also involved in NGOs, student associations, and managing non-profit foundation.

Prof. Eko Supriyanto is a biomedical engineer. He is head of Diagnostics Research Group, Universiti Teknologi Malaysia. He obtained his PhD in medical electronics from University of Federal Armed Forces, Hamburg, Germany. His research interest is engineering application in medicine. He has more than 100 international publications in the area of medical electronics, medical image processing and medical computing. He has 18 national and international innovation awards. and more than 10 patents of biomedical products.