Review On Development Of The Miniaturized Ultrasound Transducer

Hojong Choi
Department of Medical IT Convergence Engineering
Kumoh National Institute of Technology, Gyeongsangbuk-do, 39253, Republic of Korea
hojongch@kumoh.ac.kr

ARTICLE INFO

Article history:
Received 27 February 2019
Revised 5 March 2019
Accepted 21 March 2019
Published 31 March 2019

***Abstract*— Miniaturized ultrasonic (ultrasound) transducers have been widely used for ultrasound systems that provide higher spatial resolutions. In particular, the intravascular/intracardiac imaging technique requires that the ultrasonic transducer has a diameter of 2 mm or less. Miniaturized ultrasonic transducers typically have very low sensitivity and bandwidth of echo signals. Therefore, the performance optimization of ultrasonic transducers has been a critical issue to improve the image quality of the echo signals. In this review article, the development of the medical miniaturized ultrasonic transducer is reviewed and discussed.**

Keywords—miniaturized ultrasound transducer; ultrasound system; medical ultrasound

I. Introduction

Medical ultrasound imaging/therapeutic systems have been widely used for the diagnostic and treatment of lung, heart, skin, endoscopy, and intravascular, and cancer [1-4]. In particular, skin, eye, intracardiac, and intravascular application parts are suitable for high frequency ultrasound imaging applications owing to their higher spatial resolutions with relatively low penetration depth compared to low frequency ultrasound imaging applications [1].

Ultrasonic transducers are one of the most crucial components of ultrasound imaging/therapeutic systems that determine the quality and sensitivity of the returned echo signals from the targets [5]. The pulse-echo mode is one of the several evaluation modes that is similar to the electronic radar system [1]. The operating mechanisms of the pulse-echo mode are as follows: ultrasound pulses are generated from the ultrasonic transducers and are sent toward the desired targets: the reflected echo waveforms are detected by the ultrasonic transducers to produce structured images [5]. The color Doppler method provides real-time imaging, which has become a widely accepted diagnostic tool [6, 7]. In ultrasound imaging methods, a single-element transducer is used with a mechanical motor, or an array transducer with an electronic scanning method is used for a wide angle point-of-view [5].

II. METHOD

A. *Transducer design*

he high-resolution ultrasound machines for skin and eye imaging and the therapeutic ultrasound machine for prostate cancer treatment were developed by Longport and Sonacare Medical, respectively [8, 9]. These ultrasound imaging and therapeutic machines include ultrasound probes which contain imaging or high intensity focused ultrasonic transducers including electrical matching circuits and coaxial cables [8, 9]. Large electrical impedance mismatches between piezoelectric materials and system electronics are required to use an electrical impedance matching circuit inside commercial ultrasound probes [5]. The size of the piezoelectric materials, the main components of the ultrasonic transducers, is assumed to reduce while the operating frequency of the ultrasound transducer increases [10]. Therefore, several design issues, such as crosstalk, acoustic impedance, coupling coefficient, and insertion loss, must be carefully considered for performance optimization [11].

The various design parameters of the ultrasonic transducers, such as material, size, weight, thickness, and shape, could affect the acoustic parameter performances of the transducers, including their acoustic impedance, electromechanical coupling coefficient, and temperature variation [12, 13].

The tradeoff of the ultrasonic transducer design parameters enables validation of appropriate performances. For example, lead zirconate titanate provides a high electromechanical coupling coefficient (0.55), low Curie temperature (190 °C), and acoustic impedance (30 MRayls); therefore, it is suitable for high-performance imaging array applications [5]. Lithium niobate ($LiNbO_3$) crystal has a high Curie temperature (1150 °C); therefore, it can be used for high temperature applications such as detection of the heated steam in a nuclear power plant [5]. Polyvinylidene fluoride piezoelectric polymer provides a very low electromechanical coupling coefficient (0.13) but a very low acoustic impedance with flexible shapes [14]. Therefore, it can provide inherently wider bandwidth and is more suitable for the tactile sensor to measure the biological stimulation [15].

The space of miniaturized ultrasound transducers is typically limited owing to their small structure size, like a blood vessel wall, such that the performance optimization is hardly achieved [16]. In particular, a two-dimensional matrix array probe requires very thin transducers with cables [17]. For example, the small size of the piezoelectric material provides very low sensitivity because of its low breakdown voltage. Therefore, the dynamic level of the receiver electronics may typically be required to be very high (~120 dB) to receive a low amplitude level of the returned echo signal [5].

To achieve adequate echo signal sensitivity, it is important to consider the piezoelectric and matching material selection and electronics design. Therefore, the transducer equivalent circuit models, such as the KLM (Krimholtz, Leadom, and Mettaei), Mason, and Butterworth Van-Dyke (BVD) equivalent circuit models, were introduced to predict the transducer performances with the ultrasound systems [18]. The KLM and Mason models cannot be integrated with the electronics model as they both have negative capacitance values [19]. Fig. 1 shows the Mason model for a single element transducer [19]. The mechanical loading medium has two acoustic ports, one at the back and the other at the front, using mechanical ports 1 and 2 and *Z*-parameters. The electrical port has a transformer of the ratio 1:*n* and clamping capacitors (C_0 and $-C_0$). In the electrical port, there is a negative capacitance ($-C_0$), as shown in Fig. 1. Therefore, it is not practical to integrate this model with real electronics devices for performance estimation because the capacitance values are always positive.

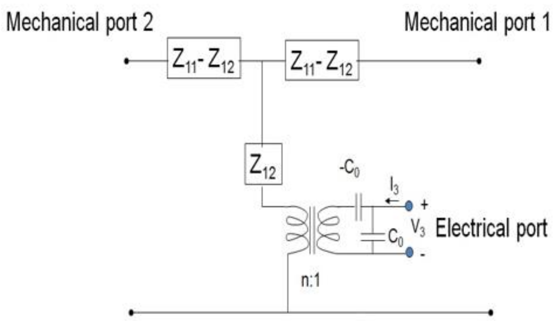

Fig. 1. *Mason model [19].*

The BVD model may be preferable when the electronic model is simulated with the transducer equivalent circuit model, because it can be easily implemented by lumped resistor-inductor-capacitor (RLC) components [19]. Fig. 2 shows the BVD model for the ultrasonic transducer that has four elements: resistor (*R*), capacitor (*C*), inductor (*L*), and a clamping capacitor (C_0) [19].

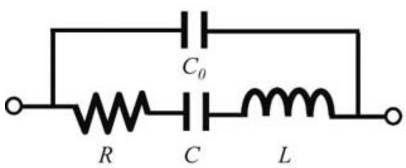

Fig. 2. *BVD model [19].*

Using finite element analysis, which uses material property and two commercial software, such as PiezoCAD (Sonic Concepts, Bothell, WA) and PZFLEX (Weidlinger Associates, Inc., Los Altos, CA), the coupling influence of the piezoelectric, matching, and backing materials in the ultrasonic transducers can be investigated to predict acoustic performances, such as sensitivity, depth of focus, echo magnitude, and bandwidth, before transducer fabrication [20, 21].

Fig. 3 shows the pulse-echo responses with the bandwidth modeled by the PiezoCAD software [22]. This program is typically used to model single-element transducers. With several material parameters, including width, length, thickness, and weight of the backing, matching, and piezoelectric materials, the simulated performances, such as pulse-echo waveform patterns and electrical impedances, could be predicted [23].

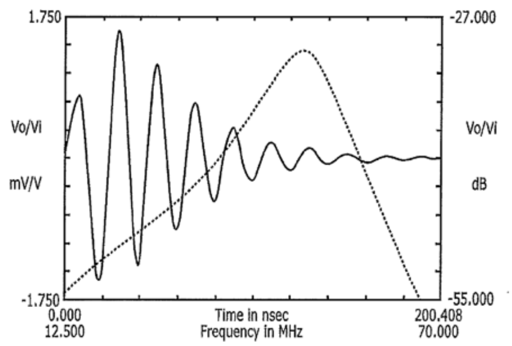

Fig. 3. *Simulated pulse-echo responses (Courtesy: Sonic Concepts)* [22].

Fig. 4 shows the beam pattern distribution of the array transducer elements generated by the PZFlex software [24]. This software is useful to model single and array transducers for various performances, such as the axial and lateral resolutions, depth of focus, and beam radiation patterns of the transmitted ultrasound and received echo signal generated by the ultrasonic transducers [25].

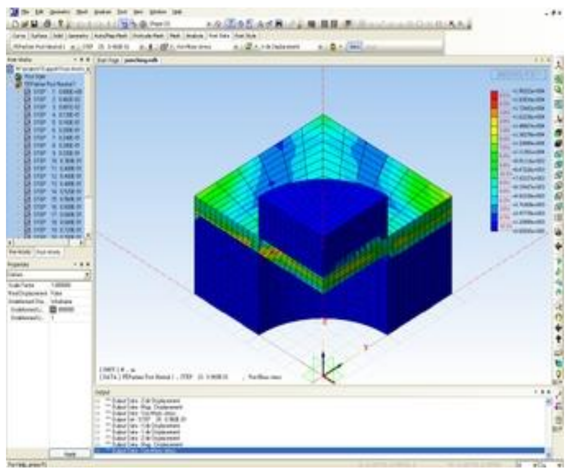

Fig. 4. *PZFlex software (Courtesy: Weidlinger Associates Inc.) [24].*

The Field II program was developed by a research lab of the Technical University of Denmark and programed by the MATLAB program [26]. This software is useful for calculating the echo signal radiation pattern and for predicting beam characteristics and profiles of ultrasonic transducers [27]. Fig. 5 shows the mathematical model of the linear array transducer in the Field II user's guide [28]. This model is shown to apodize the individual transducer elements [28].

Nondestructive testing applications are required to obtain high sensitivity and low bandwidth; medical imaging applications typically need relatively high sensitivity and broad bandwidth [29, 30]. Based on the applications, ultrasound transducers must be properly designed with the materials and shapes mentioned.

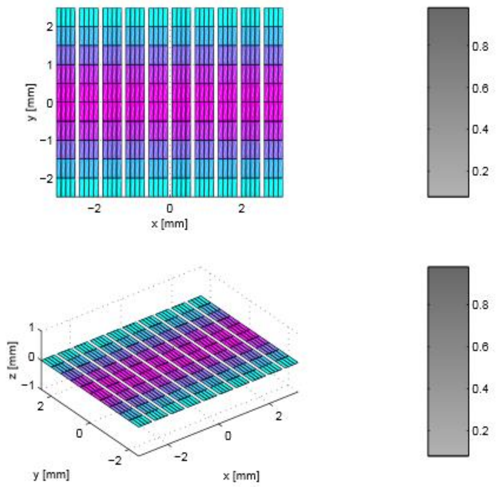

Fig. 5. *Mathematical model for the linear array transducer [28].*

B. *Systems*

Ultrasound systems are electronic systems that can control the transducer and process the data. Fig. 6 illustrates an ultrasound front-end system developed by Analog devices [31]. This block diagram also illustrates the signal path between the transducer and ultrasound systems.

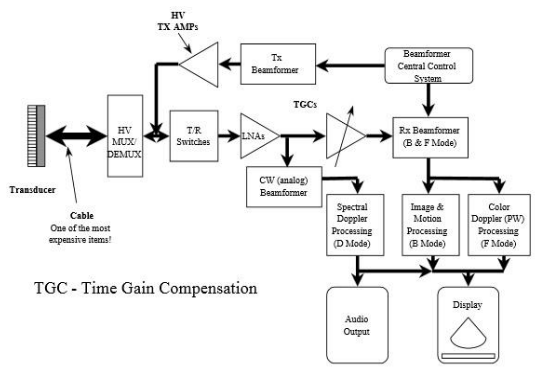

Fig. 6. *Ultrasound front-end system (Courtesy: Analog Devices.) [31]*

The cables used to connect the ultrasound transducer array into the system are one of the most expensive devices [31]. The performances of the high frequency ultrasonic transducers are even critically dependent on the length of the cables [1]. Therefore, cable size optimization is a very important issue for the performance improvement of the ultrasound transducers. To determine the cable size, the network analyzer and time domain reflectometry machines can be used for high voltage pulse transmission and low voltage echo signal detection [32]. Using the network analyzer, the small signal reflection and transmission could be measured and the large signal pulse was analyzed using time domain reflectometry [32].

Typically, electrical matching circuits between the ultrasound transducer and electronic systems should be utilized to reduce signal distortions and reflection of the ultrasound pulse and echo signals [1]. For intravascular imaging applications, the core size of the tool should be less than 2 mm, such that a multiplexer must be used to limit the number of cables [17]. Owing to the small space inside the catheters, the total cable size is limited and channel isolation between the transducer elements must be considered in the design level [33]. The long cable between the systems and the transducers must be used such that the high voltage pulse and low voltage echo signal distortions caused by the long-size cable are typically generated [33].

III. CONCLUSION

This review paper introduces miniaturized ultrasonic (ultrasound) transducers with several aspects on transducer design and systems. Ultrasonic transducers are one of the most important devices affecting the signal quality in ultrasound systems. Particularly, miniaturized ultrasonic transducers have recently been highlighted with various high frequency ultrasound applications, such as intravascular and intracardiac imaging. The design of the miniaturized ultrasound transducer must be carefully considered for performance optimization. To estimate the performances of the ultrasonic transducer, the equivalent circuit models of the transducer, such as the KLM, Mason, and BVD models, were introduced. Based on these equivalent circuit models, the PiezoCAD, PZFLEX, and Field II software can be used to estimate the performances of the ultrasonic transducers. In the system level, the effects of the coaxial cables must be considered to optimize the performances of ultrasound systems.

ACKNOWLEDGMENT

This research was supported by Kumoh National Institute of Technology (2018-104-038).

REFERENCES

[1] T.L.Szabo, Diagnostic Ultrasound Imaging: Inside Out, . London UK, Elsevier Academic Press, 2004.

[2] M. Postema, Fundamentals of Medical Ultrasound. New York, NJ, USA: Taylor and Francis, 2011.

[3] J. S. Suri, C. Kathuria, R.-F. Chang, F. Molinar, and A. Fenster, Advances in Diagnostic and Therapeutic Ultrasound Imaging. Norwood, MA, USA: Artech House, 2008.

[4] X. Wang, V. Seetohul, R. Chen, Z. Zhang, M. Qian, Z. Shi, G. Yang, P. Mu, C. Wang, and Z. Huang, "Development of a mechanical scanning device with high-frequency ultrasound transducer for ultrasonic capsule endoscopy," IEEE Trans. Med. Imaging, vol. 36, pp. 1922-1929, 2017.

[5] K. Nakamura, Ultrasonic transducers : materials and design for sensors, actuators and medical applications. Philadelphia, PA, Woodhead Publising, 2012.

[6] H. Grüll and S. Langereis, "Hyperthermia-triggered drug delivery from temperature-sensitive liposomes using MRI-guided high intensity focused ultrasound," J. Control. Release, vol. 161, pp. 317-327, 2012.

[7] J. Xia, Y. Yang, C. Hu, R. Meng, Q. Jiang, R. Liu, Y. Yu, Z. Sheng, F. Yan, and L. Zhang, "Evaluation of Brain Tumor in Small Animals Using Plane Wave-Based Power Doppler Imaging," Ultrasound Med. Biol., vol. 45, pp. 811-822, 2018.

[8] R. Illing and M. Emberton, "Sonablate®-500: transrectal high-intensity focused ultrasound for the treatment of prostate cancer," Expert Rev. Med., vol. 3, pp. 717-729, 2006.

[9] P. R. Quintavalle, C. H. Lyder, P. J. Mertz, C. Phillips-Jones, and M. Dyson, "Use of high-resolution, high-frequency diagnostic ultrasound to investigate the pathogenesis of pressure ulcer development," Adv. Skin Wound Care, vol. 19, pp. 498-505, 2006.

[10] A. Abrar, D. Zhang, B. Su, T. W. Button, K. J. Kirk, and S. Cochran, "1–3 connectivity piezoelectric ceramic–polymer composite transducers made with viscous polymer processing for high frequency ultrasound," Ultrasonics, vol. 42, pp. 479-484, 2004.

[11] J. A. Ketterling, O. Aristizabal, D. H. Turnbull, and F. L. Lizzi, "Design and fabrication of a 40-MHz annular array transducer," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 52, pp. 672-681, 2005.

[12] S.-E. Park and T. R. Shrout, "Characteristics of relaxor-based piezoelectric single crystals for ultrasonic transducers," IEEE Trans. Ultrason. Ferroelectr. Freq. Control vol. 44, pp. 1140-1147, 1997.

[13] H. L. W. Chan and J. Unsworth, "Simple model for piezoelectric ceramic/polymer 1-3 composites used in ultrasonic transducer applications," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 36, pp. 434-441, 1989.

[14] F. S. Foster, K. A. Harasiewicz, and M. D. Sherar, "A history of medical and biological imaging with polyvinylidene fluoride (PVDF) transducers," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 47, pp. 1363-1371, 2000.

[15] J. Dargahi and S. Najarian, "Theoretical and experimental analysis of a piezoelectric tactile sensor for use in endoscopic surgery," Sensor Review, vol. 24, pp. 74-83, 2004.

[16] C.R. Hill, J. C. Bamber, G. t. Harr, Physical Principles of Medical Ultrasonics. Hoboken, NJ, USA, John Wiley & Sons, Inc., 2004.

[17] B. T. Khuri-Yakub, Ö. Oralkan, A. Nikoozadeh, I. O. Wygant, S. Zhuang, M. Gencel, J. W. Choe, D. N. Stephens, A. de la Rama, P. Chen, F. Lin, A. Dentinger, D. Wildes, K. Thomenius, K. Shivkumar, A. Mahajan, C. H. Seo, M. O'Donnell, U. Truong, and D. J. Sahn, "Miniaturized Ultrasound Imaging Probes Enabled by CMUT Arrays with Integrated Frontend Electronic Circuits," IEEE Eng. Med. Bio., vol. 1, pp. 5987-5990, 2010.

[18] J. L. San Emeterio, "Determination of electromechanical coupling factors of low Q piezoelectric resonators operating in stiffened modes," IEEE Trans. Ultrason. Ferroelectr. Freq. Control vol. 44, pp. 108-113, 1997.

[19] H. Haiying and D. Paramo, "Broadband electrical impedance matching for piezoelectric ultrasound transducers," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 58, pp. 2699-2707, 2011.

[20] H. Li, Y. C. Li, D. Zhou, J. Peng, H. S. Luo, and J. Y. Dai, "Application of PMNPT single crystal in a 3.2 MHz phased-array ultrasonic medical imaging transducer," IEEE Ultrason. Symp., pp. 572-574, May 2007 [Sixteenth IEEE Int. Ferroelectr. Symp., 2007].

[21] G. Harvey and A. Gachagan, "Noninvasive field measurement of low-frequency ultrasonic transducers operating in sealed vessels," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 53, pp. 1749-1758, 2006.

[22] J. Peng, C. Chao, J. Dai, and H. L. W. Chan, "Fabrication of piezoelectric single crystalline thin layer on silicon wafer," [Online]. Available: http://www.google.com/patents/EP2028703A2?cl=en.

[23] T.L.Szabo, Diagnostic Ultrasound Imaging: Inside Out. London, UK: Elsevier Academic Press, 2013.

[24] PZFlex, LLC., PZFelx software with beam pattern distribution of the array transducer elements, [Online] Available https://pzflex.com/applications/medical/.

[25] Q. Zhou, K. H. Lam, H. Zheng, W. Qiu, and K. K. Shung, "Piezoelectric single crystal

ultrasonic transducers for biomedical applications," Prog. Mater Sci., vol. 66, pp. 87-111, 2014.

[26] J. F. Kelly and R. J. McGough, "A time-space decomposition method for calculating the nearfield pressure generated by a pulsed circular piston," IEEE Trans. Ultrason. Ferroelectr. Freq. Control vol. 53, pp. 1150-1159, 2006.

[27] J. Udesen, F. Gran, K. L. Hansen, J. A. Jensen, C. Thomsen, and M. B. Nielsen, "High frame-rate blood vector velocity imaging using plane waves: Simulations and preliminary experiments," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 55, pp. 1729-1743, 2008.

[28] J. A. Jensen. Users' guide for the Field II program [Online]. Available https://field-ii.dk/documents/users_guide.pdf

[29] H. Grüger, "Array of miniaturized fluxgate sensors for non-destructive testing applications," Sens. Actuators, A, vol. 106, pp. 326-328, 9/15/ 2003.

[30] G. M. Matte, P. L. M. J. Van Neer, M. G. Danilouchkine, J. Huijssen, M. D. Verweij, and N. de Jong, "Optimization of a phased-array transducer for multiple harmonic imaging in medical applications: frequency and topology," IEEE Trans. Ultrason. Ferroelectr. Freq. Control vol. 58, pp. 533-546, 2011.

[31] E. Brunner, "How ultrasound system considerations influence front-end component choice," Analog Dialogue, vol. 36, pp. 1-4, 2002.

[32] H. Huang and T. Bednorz, "Introducing S-parameters for ultrasound-based structural health monitoring," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 61, no. 11, pp. 1856-1863, 2014.

[33] G. Matrone, A. S. Savoia, M. Terenzi, G. Caliano, F. Quaglia, and G. Magenes, "A volumetric CMUT-based ultrasound imaging system simulator with integrated reception and μ-beamforming electronics models," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 61, pp. 792-804, 2014.