Flexible Ultrasonic Transducers and Their Performance

Kobayashi, Makiko; Shih, Jeanne-Louise; Jen, Cheng-Kuei; Ono, Yuu; Lesage, Frederic

Flexible Ultrasonic Transducers and Their Performance

M. Kobayashi[1] J.L. Shih[2], C.K. Jen[1], Y. Ono[3], F. Lesage[4]

[1]Industrial Materials Institute, Nat'l Research Council, Boucherville, Québec J4B 6Y4, Canada
[2]Dept. of Electrical and Computer Eng., McGill University, Montréal, Québec H3A 2A7, Canada
[3]Dept. of System and Computer Eng., Carleton University Ottawa, Ontario K1S 5B6 Canada
[4]Dépt. de Génie Électrique, Ecole Polytechnique de Montréal Montréal, Québec H3C 3A7, Canada

INTRODUCTION

Ultrasonic imaging technology is widely used to diagnose human health conditions noninvasively [1-3]. One critical demand is to develop large flexible ultrasonic transducers (FUTs) in an array configuration, conformable to human body shapes and capable to perform real-time imaging with high resolution. Other diagnostic functions that are convenient to patients and that are cost-effective are highly desirable. In this study, FUTs including an array form fabricated by a sol-gel spray technique [4,5] will be presented. These FUTs use 50μm thick polyimide membranes as substrates and have top and bottom electrodes of less than 20μm in thickness and a piezoelectric layer of less than 100μm thick. The flexibility is realized owing to the porosity of the piezoelectric film and the thinness of both the polyimide membrane and the electrodes. Due to the polyimide substrate, a good acoustic impedance match exists between such FUTs and human tissues. One objective of this investigation is to achieve an excellent conformability to human body parts. Another is to develop a fabrication method to fabricate large area FUTs for array applications.

The center operation frequency of interest for these FUTs ranges from 5.8 to 13.5MHz and have broad bandwidths. The fabrication method enables the FUT array to be configured by the top electrode design conveniently. Since such FUTs can be operated at 150°C, sterilization is feasible. Comparisons of the ultrasonic performance between FUTs and commercially available UTs will be discussed. Preliminary ultrasonic measurements using FUTs on polymers which have elastic properties similar to certain human tissues and that have flat and cylindrical surfaces will be reported.

FABRICATION AND EVALUATION OF FUTS

The detailed fabrication process of the sol-gel spray technique can be found from previous publications [4,5]. Piezoelectric lead-zirconate-titanate (PZT) powders were purchased. Fine and submicron size powders were dispersed into PZT sol-gel solution by the ball milling method to achieve the paint for subsequent spray. It is known that a piezoelectric ceramic layer needs both top and bottom electrode to function as an UT. Since polyimide membrane is an insulator, it is required to fabricate the bottom electrode layer onto the polyimide membrane before the spray coating of piezoelectric PZT/PZT [4,5] composite film. Two approaches are used. One uses colloidal spray of ≤2μm thick silver layer and the other involves electroless plating of a ~1μm thick nickel layer. An airbrush was then used to spray the PZT/PZT sol-gel composite directly onto the bottom electrodes of the polyimide substrate. Thin copper foil or paper masks served as the shadow mask during the spray coating. The PZT sol-gel solution contributed as a bonding material between the PZT powder and the bottom electrode. After each PZT/PZT coating, thermal treatments were carried out. Multiple layers were made in order to reach a desired film thickness leading to proper ultrasonic operating frequencies of the FUTs. Next, corona poling is used to obtain piezoelectricity of the PZT/PZT film. Finally, the top electrode pattern is made with silver paste paint or a colloidal silver spray with another mask. Such an electrode fabrication approach enables to achieve desired sensor array configurations easily and economically. Certainly the electrical impedance matching between each UT and the pulser/receiver needs to be considered.

A simple evaluation of the above mentioned FUTs based on the comparison with commercially available broadband UT will be illustrated. Since fused quartz has low ultrasonic attenuation below 30MHz, a plate with a 6.55mm thickness and a 50.8mm diameter and polished at both the top and bottom surfaces is used as the sample for study of the frequency response of the FUTs. The results will be compared to those measured by a commercial broadband UT. All measurements will be performed in pulse/echo mode.

Four FUT Linear 1-D Array

Fig.1 shows a FUT with a colloidal silver sprayed bottom electrode of ≤2μm thickness. The thickness of the piezoelectric ceramic layer is 60μm. The four top electrodes forming the 4-UT linear 1-D array were made using silver paste each with 20μm in thickness. The average diameter of the top electrode is ~8.5mm. The flexibility of this FUT can be seen from Fig.2 which shows a curvature of 13mm in its diameter. Its conformability to a human nose is shown in Fig.3. Fig.4 presents the measured ultrasonic signals using one of the four FUTs in Fig.1 with a gel couplant between the FUT and the 6.55mm thick fused quartz plate. L^n is the nth round trip echo through the plate thickness. The center frequency and 6dB bandwidth of the L^1 echo are 12.2MHz and 9.0MHz, respectively. This FUT has 25dB less strength than a commercial broadband UT.

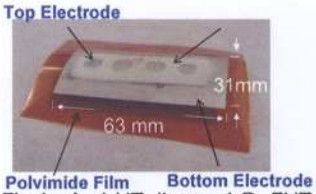

Fig.1. A 4-UT linear 1-D FUT array.

Fig.2. Flexibility of the 4-UT linear 1-D FUT array shown in Fig.1.


Fig.3. Conformability of the FUT array shown in Fig.1.

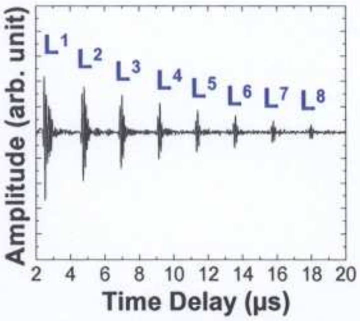

Fig.4. Measured ultrasonic signals on a fused quartz plate.

5 by 6 2-D FUT Area Array

In order to demonstrate that the sol-gel spray technique can be used to fabricate a large area, 2-D FUT array, a polyimide membrane with a size of 85mm by 75mm is used. First electroless plating of ~1μm thick nickel is carried out at both sides of the polyimide. Then a piezoelectric PZT/PZT composite film of ~90μm thick with a size of nearly 80mm by 70mm is made onto one nickel film side. The other side serves as the bottom electrode of the FUT. After the poling of the film, a 25μm thick copper mask shown in Fig.5 is made and used during the colloidal spray of the ≤2μm thick top silver electrode using an air brush. The 5 by 6 FUT array is shown in Fig.6. Each element has an area of 10mm by 10mm. The separation distance between each adjacent element is 2mm. Certainly, each element can be made as small as 1mm by 1mm, and the choice will be based on the specific application. The flexibility of such a FUT 2-D array is demonstrated in Fig.7. At present the 1-D FUT array shown in Fig.1 has higher flexibility than this 2-D array.

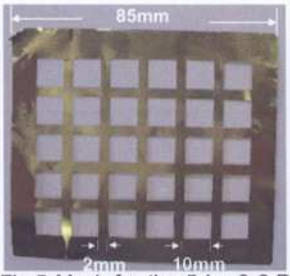

Fig.5 Mask for the 5 by 6 2-D FUT array.

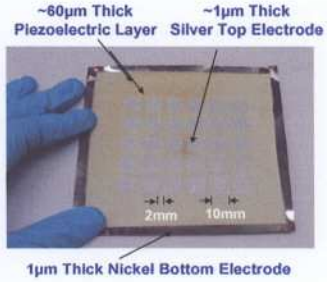

Fig.6 A 5 by 6 2-D FUT array.

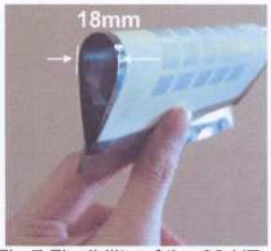

Fig.7 Flexibility of the 30-UT FUT.

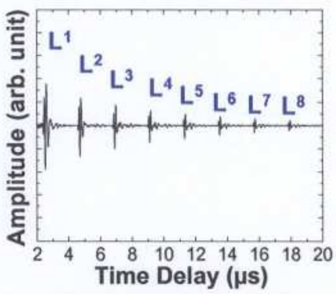

Fig.8. Measured ultrasonic signals on a fused quartz plate.

Fig.8 shows the measured ultrasonic signals using one of the 5 by 6 FUT array near the center in Fig.6 with a gel couplant between this FUT and the 6.55mm thick fused quartz plate. The center frequency and 6dB bandwidth of the L^1 echo are 5.8MHz and 8.5MHz, respectively. This FUT has 35dB less strength than a commercial broadband UT.

Ring FUT

In diagnostic ultrasonic imaging, ring or annular transducers are often required [1,2,6,7]. One merit of the presented fabrication technology is that the top electrode, which defines the transducer array configuration, can be conveniently made using the colloidal silver spray method. Because of the ring shape, two masks made of the same material as the

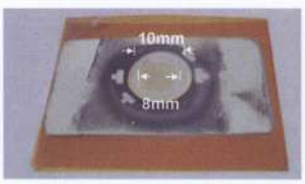

Fig.9. A ring shape FUT.

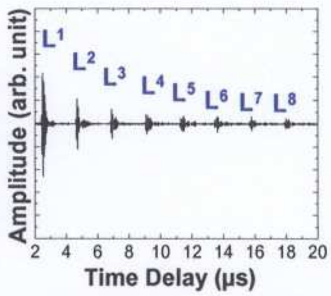

Fig.10. Measured ultrasonic signals on a fused quartz plate

one shown in Fig.5 need to be used to fabricate a complete ring FUT with alignment marks outside of the ring as shown in Fig.9.

Fig.10 shows the measured ultrasonic signals using the ring FUT shown in Fig.9 with a gel couplant between the FUT and the 6.55mm thick fused quartz plate. The center frequency and 6dB bandwidth of the L^1 echo are 13.5MHz and 5.9MHz, respectively. This FUT has 50dB less strength than a commercial broadband UT.

ULTRASONIC MEASUREMENTS

In order to validate the performance of the FUT array, ultrasonic measurements using polymers, which have the elastic properties close to several human tissues, have been used in the experiments. Table 1 provides the elastic properties of plexiglass (PMMA) [8], polyimide (VESPEL), polyetheretherketone (PEEK) and high density polyethylend (HDPE) [9], and human parts such as bone, liver, kidney, fat, blood [10] and muscle [11]; However, the measurement data for PMMA plate and VESPEL rod will be presented only.

Material	ρ (kg/m³)	V_L (m/s)	V_S (m/s)	Z_L (10^6 kg/m²s)	Z_S (10^6 kg/m²s)
PMMA	1185	2700	1330	3.200	1.576
VESPEL	1421	2414	1014	3.430	1.441
PEEK	1290	2549	1125	3.288	1.451
HDPE	950	2292	922	2.177	0.876
Bone	1380-1810	4080	---	5.630-7.385	---
Liver	1060	1570	---	1.664	---
Kidney	1040	1560	---	1.622	---
Fat	920	1450	---	1.334	---
Blood	1060	1570	---	1.664	---
Muscle	1060	1630	---	1.728	---

Flat PMMA Plate with An Artificial Defect

Fig.11. A schematic of a FUT to detect a hole in PMMA plate.

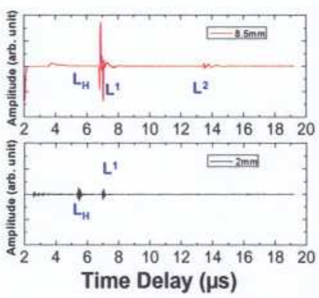

Fig.12. Measured ultrasonic signals

Fig.11 shows a schematic of a PMMA plate with a drilled, non-flat bottom hole of 2mm in diameter on the opposite side of the FUT location. When one of the FUT 1-D array with an 8.5mm diameter active area (top electrode size) is positioned right on the top of the hole as shown in the upper figure of Fig.11, the hole is barely detectable in the upper curve of Fig.12. Then, a 2mm diameter top electrode is made using the silver paste. When this FUT is positioned right on the top of the hole as shown in the lower figure of Fig.11, the hole can be clearly seen, as indicated as L_H in the lower figure of Fig.12. This demonstrates that the FUT fabrication technology presented here may be tailored by changing the transducer active area conveniently to detect small defects.

Cylindrical VESPEL Rod

In order to illustrate that FUTs can be used to measure human body parts with curved surfaces, a cylindrical VESPEL rod with a diameter of 17.5mm is used. Fig.13 shows that the 5 by 6 2-D FUT array shown in Fig.6 is wrapped around the VESPEL rod with a couplant underneath. One element is used to perform the measurement. The measurement result is given in Fig.14. L^n is the nth round trip echo through the rod diameter. The center frequency and 6dB bandwidth of the L^1 echo are 1.7MHz and 2.6MHz, respectively.

Fig.13. A VESPEL rod is wrapped around by the 5 by 6 FUT array.

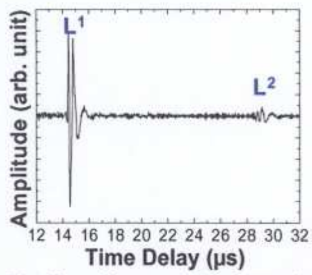

Fig.14. Measured ultrasonic signals in the VESPEL rod.

CONCLUSIONS

Flexible ultrasonic transducers (FUTs) and their performances have been presented. A sol-gel sprayed technique is used to fabricate the FUT which consists of a 50μm thick polyimide membrane, a piezoelectric ceramic layer of less than 100μm, top and bottom electrodes of thickness less than 20μm. The thin electrodes are made of silver or nickel. The flexibility is realized owing to the porosity of piezoelectric film and the thinness of polyimide membrane and electrodes. Such FUT may be conformed to human body shapes. The array configuration can be achieved by arranging the top electrodes. A 4 UT 1-D array, a 5 by 6 2-D array and a ring FUTs were realized. Using a fused quartz plate the ultrasonic performance of these FUTs have been evaluated. The center frequencies and 6dB bandwidth range from 5.8MHz to 13.5MHz and from 5.9MHz to 9.0MHz, respectively based on the measurement results on 6.55mm thick fused quartz plate. Preliminary results indicated that these FUTs have more than 25dB weaker signal than commercial available UTs having a similar active area. The improvement of the piezoelectric strength of these

FUTs will be continuously carried out. Since many current ultrasonic systems are equipped with nearly 100dB dynamic measurement range, these FUTs may serve as excellent UTs for diagnostic imaging purposes.

Ultrasonic measurements using FUTs on polymers, which have elastic properties close to certain human tissues, were performed. It was demonstrated that FUTs can be used to detect defects in flat PMMA plates and to conduct measurements on cylindrical VESPEL rods.

ACKNOWLEDGEMENTS

The authors would like to thank the technical assistance of K.-T. Wu and L. Song and financial support from Natural Science and Engineering Research Council.

REFERENCES

[1] T.L. Szabo, "Diagnostic ultrasound imaging: Inside Out", Academic Press, NY, 2004.

[2] K.K. Shung "Diagnostic Ultrasound: Imaging and Blood Flow Measurements" Francis Taylor: CRC Press, Boca Raton, FL, 2005.

[3] E.D. Light, S. Mukundan, P.D. Wolf and S.W. Smith, "Real-time 3D intracranial ultrasound", *Ultrasound Med. Biol.*, vol.33, pp.1277-84, 2007.

[4] M. Kobayashi, C.-K. Jen, and D. Lévesque, "Flexible ultrasonic transducers," *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*, vol.53, pp.1478-1486, 2006.

[5] C.-K. Jen and M. Kobayashi, "Integrated and flexible high temperature piezoelectric ultrasonic transducers", Chapter 2 in *Ultrasonic and Advanced Methods for Nondestructive Testing and Material Characterization*, Ed. by C.H. Chen, World Scientific Publishing, New Jersey, pp.33-55, 2007.

[6] X.M. Yang, M.L. Li, and L.V. Wang, "Ring-based ultrasonic virtual point detector with applications to photoacoustic tomography," *Appl. Phys. Lett.*, vol.90, pp.251103, 2007.

[7] C.H. Hu, K.A. Snook and K.K. Shung. Development of a high frequency annular array imaging system II: digital beamformer design. *IEEE Trans Ultra. Ferroelect. Freq. Cont.* vol.53, pp. 309-316, 2006.

[8] C.-K. Jen, D. Ramos-França, Z. Sun and I. Ihara, "Clad polymer buffer rods for polymer process monitoring", *Ultrasonics*, vol.39, pp.81-89, 2001.

[9] A. Briggs, "Acoustic Microscopy", Clarendon Press, Oxford, p.103, 1992.

[10] J.L. Prince and J.M. Links, "Medical Imaging Signals and Systems", Pearson Prentice-Hall, Upper Saddle River, NJ, p.319, 2006.

[11] A.J. Mortimer, "Physical characteristics of ultrasound", Chapter 1 in Essentials of Medical Ultrasound, Ed. by M.H. Repacholi and D.A. Benwell, Humana Press, Clifton, NJ, p.31, 1982.