Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

High Frequency Ultrasound Imaging by Scanning a Single-element Transducer

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***Abstract*—Mechanical scanning of a single-element transducer and electronic scanning of an array transducer have been mostly utilized for high frequency ultrasound imaging. Considering that mechanical scanning systems are bulky and development of high frequency transducer arrays and their imaging systems are sophisticated and expensive, here we propose a novel approach, where a scanning forward-looking (FL) single-element transducer embedded in a steel pipe is driven by a tubular piezoelectric actuator, to get both B-scan and C-scan images. In the work, a positioning system composed of a two-dimensional position sensitive detector (PSD) is used to obtain the accurate information of the transducer position in real time. Ultrasonic signals and position information are acquired continuously while scanning the transducer across a tungsten wire phantom to reconstruct B-scan and C-scan images. The imaging performance of the scanning system is compared with traditional scanning imaging results. This work demonstrates that it is feasible and promising to obtain B-scan and C-scan high frequency ultrasound imaging by simply scanning a single-element transducer driven by a tubular piezoelectric actuator.**

Keywords—High-frequency ultrasound imaging, C-scan, tubular piezoelectric actuator

I. INTRODUCTION

High frequency ultrasound imaging has received increasing attention and application in biomedical research and endoscopic and minimally invasive clinical practice [1]. High frequency ultrasound images can be obtained either by a single-element transducer mechanical scanning [2], or by an array electronic scanning [3, 4]. However, mechanical scanning systems are mostly bulky. On the other hand, the development of high frequency transducer arrays and their imaging systems are sophisticated and expensive. Some transducers with specific structural design have been proposed and investigated in the past few years. For example, a single-element transducer integrated in a steerable catheter together with an OSS fiber has been proposed for forward-looking intravascular ultrasound (FL-IVUS) imaging [5]. Unfortunately, it is difficult to realize fast ultrasound imaging on the grounds that obtaining one frame image requires manually steering the catheter which takes about a minute to complete.

A scanning fiber endoscopy (SFE) technology developed by Eric J. Seibel at University of Washington, using a scanning cantilevered optical fiber instead of a fiber bundle or a pixel-array camera, has solved the problem of mutual restriction between resolution or field of view (FOV) and the catheter diameter [6]. Using the same mechanism ultrasound C-scan imaging can be achieved by scanning a high frequency single-element transducer.

In this work, we propose a strategy for both B-scan and C-scan high frequency ultrasound imaging using a coaxial scanner design consisting of a high frequency single-element transducer mounted at a steel pipe tip and a tubular piezoelectric actuator. A positioning system composed of a two-dimensional position sensitive detector (PSD), a single-mode optical fiber and a optic light source was set up to obtain the positon of the transducer. While the transducer is vibrating driven by the tubular piezoelectric actuator, ultrasound A-lines are acquired and mapped to a specific position in the B-scan/C-scan plane combined with the data from the PSD. To test the functionality of the scanner, we performed a preliminary imaging test using a wire phantom submerged in water.

II. METHODS

Fig. 1(a) shows the construction of the designed scanner, which consists of a central needle-type probe cantilevered from the tip of a tubular piezoelectric (PZT-5H) actuator (PiezoDrive Pty Ltd., Australia). A FL single-element transducer is mounted at the tip of a steel pipe, as shown in Fig. 1(b) which is an enlarged view of the probe tip in Fig. 1(a).

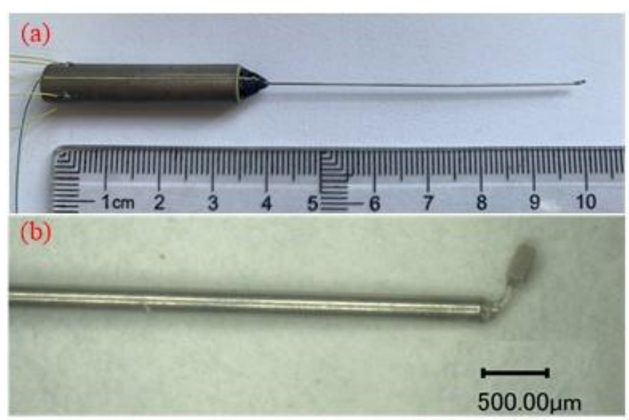

Fig. 1. (a) The designed scanner consisting of a needle-type probe cantilevered on the tip of a tubular piezoelectric actuator. (b) A FL single-element transducer mounted at the tip of a steel pipe.

The work was financially supported by National Natural Science Foundation of China under Grant Number of 51675278 and the Project of Key Research and Development Plan of Jiangsu Province under Grant Number of BE2017730.

The high frequency FL transducer, manufactured at Acoustic Life Science Corp., has a rectangle-shaped aperture measuring 0.4 mm×0.5 mm and a center frequency of 35 MHz. The tubular piezoelectric actuator is a radially polarized thin cylinder with four external electrodes and a internal electrode. When a alternative voltage is applied on one of the external electrodes, the tube wall expands and shrinks causing a contraction and deflection at the tip. When the base of the tube is fixed, the tip translations Δx and Δy are approximately

$$\Delta x = V_x \frac{2\sqrt{2}d_{31}L^2}{\pi Dh} \qquad \Delta y = V_y \frac{2\sqrt{2}d_{31}L^2}{\pi Dh} \tag{1}$$

where Δx and Δy are the x and y axis deflection, d_{31} is the piezoelectric strain constant, L is the length of the tube, D is the outside diameter, h is the tube thickness, and V_x and V_y are the electrode voltages which are applied oppositely to either side of the tube [7].

The mechanism of the coaxial scanner is that needle-type ultrasound probe vibrated laterally at mechanical resonance which is driven by the tubular piezoelectric actuator with four electrodes to scan the FL single-element transducer in two dimensions above the object being inspected [8]. By electronically driving the tubular piezoelectric actuator near the probe's 1st-mode resonance, the vibration motion of the probe tip experiences a mechanical gain of 40-60 dB. FEM simulation of the scanner was conducted for various conditions to maximize its scanning range by using the COMSOL Multiphysics software (COMSOL Inc., Sweden), the optimal results are shown in Table I.

TABLE I. SCANNER COMPONENTS

Part	Dimensions	Material
Piezo tube	7 mm OD, 5.6 mm ID, 35 mm long	PZT-5H
Drive electrodes	5 μm thickness	Nickel
Probe housing	0.4 mm OD, 0.2 mm ID, 60 mm long	Steel
Transducer	0.4 mm×0.5 mm aperture	Composite PMN-PT

With the probe vibration, B-scan and C-scan can be realized by generating line scan patterns and spiral scan patterns, respectively, under different driving controls. A spiral scan pattern can be produced by applying single frequency cosine and sine signals with slowly varying amplitudes to the x and y axis while a line scan pattern is obtained by applying single frequency cosine or sine signal with invariant amplitude to only one axis. In this work, the tubular piezoelectric actuator is driven by TD250 Amplifier (PiezoDrive Pty Ltd., Australia) which amplifies the drive voltage signals generated by Function Generator AFG1062 (Tektronix Inc., USA).

The key of the pulse-echo ultrasound imaging is to acquire the mapping of A-scan lines and the transducer position by means of either scanning the transducer in a freehand form with the detection of the transducer position in space or actively controlling the motion of the transducer [9]. It is difficult for us to exactly know the motion of the transducer in this scanning ultrasound imaging system because the motion speed of the transducer varies with the change of resistance in water. We set up a positioning system consisting of a PSD (DL100-7, First Sensor Technics Ltd., German), a single-mode optical fiber (Pi-optics Ltd., China) and an optic light source (ZYEC1, Zeiyue Inc., China). The two-dimensional PSD based on the lateral optoelectronic effects is adapted in this work to fulfill the requirements of high precision and real-time detection of the 2D beam position [10]. The fiber with diameter of standard 125 μm is attached to the needle and vibrates together, working as an optical waveguide that transmits red light with 1 mW power from the optic light source to the PSD. We fix the PSD to make the chip surface perpendicular to the probe at rest, in which case the lateral motion of the probe can be calculated from the movement of the spot of the optical fiber on the PSD chip while the probe and the optical fiber are vibrating together.

The imaging performance of the scanner is tested by imaging a wire phantom with both horizontal and vertical relative wire distances of 0.5 mm. The wire phantom (Fig. 2) consists of five parallel tungsten wires with a diameter of 15 μm.

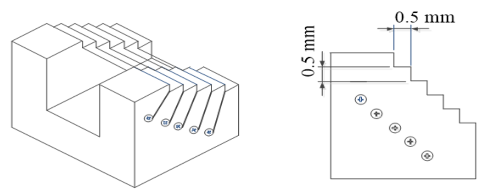

Fig. 2. Design of the tungsten wire phantom with both horizontal and vertical relative wire distances of 0.5 mm.

The imaging set-up is shown in Fig. 3. The reconstruction of the wire phantom is achieved by mapping the received A-lines to a specific position detected by the PSD. While the transducer is submerged in water and scanning, the Verasonics Vantage 64LE system (Verasonics Inc., USA) transmits and receives ultrasound signals and triggers the control system to sample the PSD signals at the pulse repetition frequency (PRF) of the transmit pulses. The ultrasound excitation used is a 2 cycle sinusoidal pulse at 35 MHz with a PRF of 8 kHz, while the position data are acquired at 8 kHz and then transferred to the computer for reconstruction.

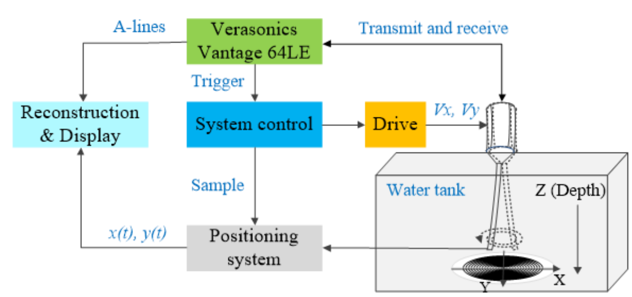

Fig. 3. Schematics of proposed scanning ultrasound imaging system.

III. RESULTS AND DISCUSSION

The 60-mm-long needle-type probe vibrates in water at the first-mode resonance frequency of 80 Hz driving the transducer scanning in a line pattern or a spiral pattern. At this frequency the probe tip reaches a scanning range of 4 mm (width of the line or diameter of the spiral pattern). B-scan ultrasound imaging experiments were performed with the FL single-element transducer moving step by step or scanning driven by the tubular piezoelectric actuator over the tungsten wire phantom. The reconstructed images of the wire phantom obtained by the two scanning modes are shown in Fig. 4 respectively.

C-scan images at different depths by the vibrating the FL single-element transducer have been successfully obtained. Acquired A-lines of one frame are shown in Fig. 5(a). By mapping the A-lines to the detected transducer position, we reconstructed four of the tungsten wires at the depths of 1.3059 mm, 1.7618 mm, 2.3531 mm and 2.8706, as shown in Fig. 5(b)-(e), respectively. In addition, video imaging at 0.4 fps and 120 lines per image (240×240 pixels) is achieved.

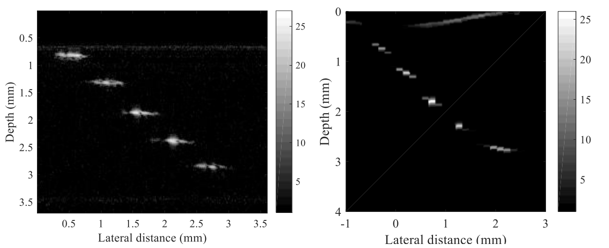

Fig. 4. B-scan images of wire phantom by the same single-element transducer by moving the transducer step by step (left) and vibrating the transducer (right).

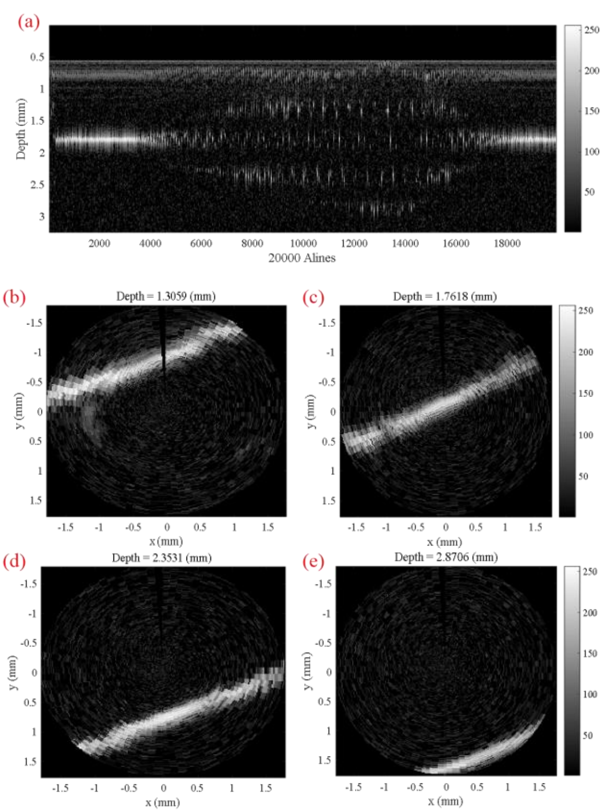

Fig. 5. (a) Ultrasound A-lines aquired while scanning the transducer across the wire phantom in a spiral pattern. (b)-(e) Four reconstructed images of the phantom in C-scan mode at the depths of 1.3059 mm, 1.7618 mm, 2.3531 mm and 2.8706, respectively.

The strategy proposed is suitable for high frequency C-scan ultrasound imaging because the high frequency transducers are easier to be fabricated such small and light that able to be mounted at the tip of a capillary steel pipe which vibrates driven by a tubular piezoelectric actuator. The positioning system built with PSD is a preliminary method to verify the feasibility of vibrating a FL single-element transducer to achieve fast ultrasound imaging. However, the attachment of the fiber shifts the resonant frequency of the scanner and increases complexity and asymmetry of the scanner. Moreover, the direction of the probe tip has not been taken into account, which reduces the accuracy of reconstruction results.

IV. Conclusion and Further Work

In conclusion, we have demonstrated that high frequency ultrasonic B-scan and C-scan imaging by scanning a high frequency FL single-element transducer driven by tubular piezoelectric actuator is feasible. Future work will include improvement of the positioning system using the look-up table method to get more accurate positioning information and imaging of more complex phantom design to evaluate the performance of this high frequency ultrasound imaging system. Furthermore, we will investigate how to obtain accurate reconstruction results without positioning system. The accurate dynamics model of the scanner will aid in building the connections between the drive voltage and the transducer position.

Acknowledgment

Special thanks to Xiang Li and Zhongxia Lin at Acoustic Life Science Corp. for the ultrasound transducer fabrication and fixing at the tip of the steel pipe. This work is financially supported by the National Natural Science Foundation of China (Grant No. 51675278) and the Project of Key Research and Development Plan (Social Development) of Jiangsu Province (Grant No. BE2017730).

References

[1] J. C. Lacefield, "Ultrasound micro-imaging," Encyclopedia of Cancer. 3rd ed., vol. 1. Springer, Berlin: Heidelberg, 2011, pp. 3836-41.

[2] J. L. Evans, K. H. Ng, M. J. Vonesh, B. L. Kramer, S. N. Meyers,T. A. Mills, et al., "Arterial imaging with a new forward-viewing intravascular ultrasound catheter, I. initial studies," Circulation, vol. 89, no. 2, pp. 712-7, February 1994.

[3] E. C. Nestor, E. Payam, W. Robert, H. Jung, T. C. Chi, A. W. Jay, "Forward-looking 30-MHz phased-array transducer for peripheral intravascular imaging," Sensors and Actuators A: Physical, vol. 280, pp. 145-63, July 2018.

[4] F. L. Degertekin, R. O. Guldiken, M. Karaman, " Annular-ring CMUT arrays for forward-looking IVUS: transducer characterization and imaging," IEEE Trans Ultrason Ferroelectr Freq Control, vol. 53, no. 2, pp. 474-82, February 2006.

[5] J. Janjic, M. D. Leistikow, A. Sakes, F. Mastik, N. D. Jong, J. G. Bosch, et al. "3D Imaging with a single-element forward-looking steerable IVUS catheter: initial testing," Ultrasonics Symposium IEEE, September 2016.

[6] E. J. Seibel, Q. Y. J. Smithwick, C. M. Brown, P. G. Reinhall, "Single-fiber flexible endoscope: general design for small size, high resolution, and wide field of view," Proc. Spie, vol. 4158, pp. 29-39, January 2001.

[7] S. O. R. Moheimani, "Invited review article: accurate and fast nanopositioning with piezoelectric tube scanners: emerging trends and future challenges, " Rev. Sci. Instrum., vol. 79, dol. 071101, July 2008.

[8] M. L. Cameron, J. E. Christoph, D. S. Timothy, H. Fritjof, J. S. Eric, "Scanning fiber endoscopy with highly flexible, 1 mm catheterscopes for wide-field, full-color imaging," Journal of Biophotonics, vol. 3, no. 5-6, pp. 385-407, March 2010.

[9] T. L. Szabo, Diagnostic Ultrasound Imaging: Inside Out, 2nd ed., 2014.

[10] H. Liu, Y. Xiao, Z. Chen, "A High Precision Optical Position Detector Based on Duo-lateral PSD," International Forum on Computer Science-technology & Applications, January 2009.