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● *Technical Note*

LOW-COST 3-D HYDROPHONE SCANNING TANK WITH MATLAB GUI CONTROL

Sam Clinard,[*,†] Erin Wettstone,[*] David Moore,[*,‡] John Snell,[*,‡]
Frederic Padilla,[*,§] and Matt Eames[*,‡]

[*] FUS Foundation, Charlottesville, Virginia, USA; [†] Department of Biomedical Engineering, University of Utah, Salt Lake City, Utah, USA; [‡] Department of Neurosurgery, University of Virginia School of Medicine, Charlottesville, Virginia, USA; and [§] Department of Radiology, University of Virginia School of Medicine, Charlottesville, Virginia, USA

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Abstract—The Focused Ultrasound Foundation has developed a low-cost, validated, open-source hydrophone scanner for the spatial characterization of ultrasound transducers. Assembly instructions and a MATLAB control graphical user interface are provided such that the device can be easily replicated for less than $1000 in roughly 40 person-hours. The low-cost scanning tank's performance was compared with data collected with a commercial automated scanning tank. Pressure measurements of a focused transducer and a planar transducer had less than a 10% difference between the two scanning systems. Two-dimensional automated scans (20 × 20 mm at 0.25-mm resolution) took the low-cost scanning tank 45 min compared with the commercial system's 30 min. A reproducibility study found that the low-cost scanner made consistent peak negative pressure measurements as reflected by the low coefficient of variation for both focused (1.88%) and planar (0.98%) transducers. The low-cost scanner described here is a viable alternative for ultrasound laboratories needing efficient, accurate characterization of ultrasound transducers. (E-mail: Sam.Clinard@utah.edu) © 2021 World Federation for Ultrasound in Medicine & Biology. All rights reserved.

Key Words: **Ultrasound, Hydrophone, Acoustics, Transducers, Open source, Acoustic field measurement.**

INTRODUCTION

Motorized 3-D hydrophone scanning tanks are standard equipment in ultrasound research labs and are used to characterize ultrasound transducers. These tanks allow the recording of a transducer's output pressure in 3-D space so that the device's acoustic field and other pressure output characteristics can be visualized and quantified. A commercial scanning tank and software can cost tens of thousands of dollars, often representing a significant portion of a nascent lab's start-up cost or a sizable portion of a grant application. Labs may, alternatively, commit the time to build a homegrown system at a significantly lower cost. Described here is a validated 3-D scanning tank with assembly instructions and a basic MATLAB (The MathWorks, Natick, MA, USA) control graphical user interface (GUI) that can be built for less than $1000 (excluding hydrophone, oscilloscope, function generator and MATLAB license, most of which engineering research labs/institutions have in place) in roughly 40 person-hours.

Address correspondence to: Sam Clinard, 1230 Cedars Court, Suite 206 Charlottesville, VA 22903, USA. E-mail: Sam.Clinard@utah.edu

METHODS

Materials for assembling the hydrophone scanning tank were sourced from online vendors and consisted of four NEMA 17 stepper motors, limit switches, 20-mm aluminum extrusion, linear bearings and associated fittings, an Arduino microcontroller and accompanying CNC "shield," cabling and 3-D-printed parts (Fig. 1). A bill of materials containing the parts, vendors, and approximate pricing is available through the corresponding author. A user manual is also available describing how to build and operate the scanner.

A MATLAB graphical user interface (GUI) orchestrates the scans, setting and controlling the function generator, oscilloscope and Arduino microcontroller. The GUI currently uses embedded programming intrinsic to a Tektronix TDS2001C Oscilloscope and a Tektronix AFG3001C (Tektronix, Beaverton, OR, USA); however, the program can be easily modified to control other generators/oscilloscopes. The GUI sends ASCII commands to the Arduino containing the axis, direction and the number of steps to move. The Arduino drives four NEMA (National Electrical Manufacturers Association)

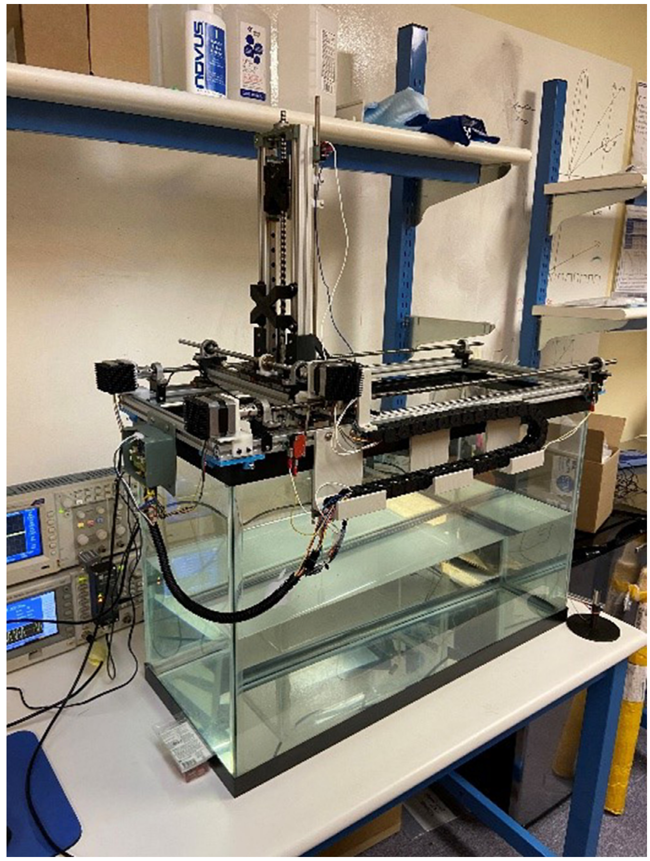

Fig. 1. Focused Ultrasound Foundation (FUSF) low-cost hydrophone scanner.

14 stepper motors by a Synthesos gShield to achieve three translation axes. The lead screws have a 2-mm pitch, which results in a 0.01-mm resolution with a 200 steps/rotation motor.

Two transducers were scanned using both the home-made low-cost scanning tank and a commercially available automated 3-D scanning tank (AIMS III, Onda Corp, Sunnyvale, CA, USA) to assess the system's performance. The commercial scanner's highest resolution is 5.5 μm. Both transducers—a focused 350-kHz center frequency transducer with a transducer radius of 22 mm and radius of curvature of 31.5 mm, and a plane 1.1-MHz center frequency transducer 11 mm in diameter—were manufactured by Sonic Concepts, Inc. (Bothell, WA, USA). With both scanning tanks, the same equipment was used to scan the pressure fields from the transducers: Onda needle hydrophone (diameter = 0.4 mm, HNA-400), function generator (TEK AFG3001C), oscilloscope (TEK TDS2001C). Scans were acquired with 0.25-mm spatial steps to have a resolution on the order of a wavelength. Both scanners completed 1-D scans to center the hydrophone on the focal point or natural focus. In addition, time of flight was used to ensure the hydrophone was axially positioned consistently with the two systems.

Pressure radiated by the transducers was modeled using either the analytical O'Neil model (O'Neil 1949) for the 350-kHz focused transducer or the hybrid angular spectrum (HAS) numerical method (Vyas and Christensen 2011) for the plane 1.1-MHz transducer.

RESULTS

Acquisition time

The low-cost scanning tank completed the measurement of a 20 $\times$ 20-mm scan in 45 min compared with the commercial system's 30 min. The low-cost scan times could potentially be improved through more efficient programming; however, the slower scan time does reduce movement artifacts that are often seen in the commercial system's scan. For this reason, the commercial system has a delay feature to allow ringdown at each point, which, when used, leads to scan times comparable to those of the low-cost scanner.

Pressure measurements for a focused transducer

Both systems were used to scan a 350-kHz focused transducer in the lateral and axial planes. The 2-D lateral (xy) scans and 2-D axial (xz) scans (Fig. 2a−d) have qualitatively

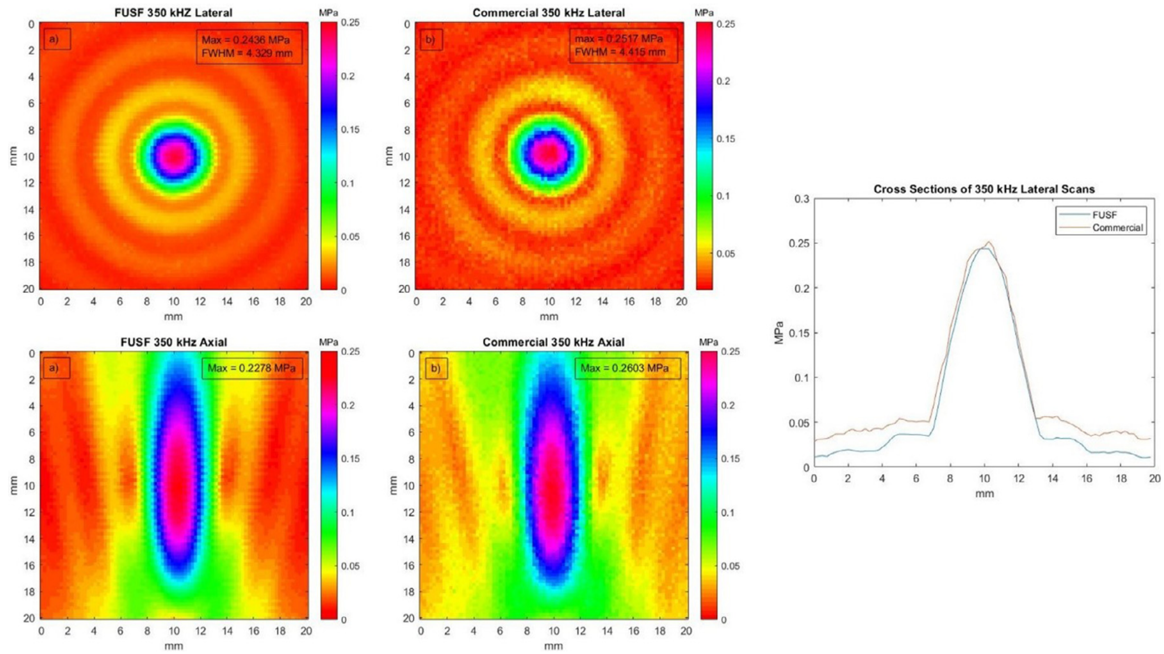

Fig. 2. Top left: Side-by-side comparison of transverse 20 × 20-mm 0.25-mm resolution negative pressure (MPa) scans of the 350-kHz focused transducer with the (a) Focused Ultrasound Foundation (FUSF) low-cost model and (b) commercial model. Bottom left: Side-by-side comparison of axial 20 × 20-mm 0.25-mm-step size-negative pressure (MPa) scans of the 350-kHz focused transducer with the (a) Focused Ultrasound Foundation (FUSF) low-cost model and (b) Commercial model. Right: Cross section through maximum pixel value of transverse images. Agreement in pressure value and location of lobes is observed.

Table 1. Comparison of maximum peak negative pressure and FWHM of cross sections from Figure 2 reveals agreement between systems*

	FUSF	Commercial	Difference
xy Maximum peak negative pressure (MPa)	0.2436	0.2517	3.3%
xy Cross section FWHM (mm)	4.329	4.415	2.0%
xz Peak negative pressure (MPa)	0.2278	0.2603	13.3%

FWHM = full width half-maximum; FUSF = Focused Ultrasound Foundation.

* The higher percentage difference in peak negative pressure measured in axial scans is due primarily to variation in position relative to the axis.

similar peak negative pressure and focal size defined as the −6-dB focal width of the beam. A horizontal cross section through the lateral scan's peak maximum pixel was extracted to compare the two scans (Fig. 2e). Measurements with both systems provided peak pressure with less than 10% difference (Table 1), primarily because of variation in hydrophone positioning and noise, which could be reduced by signal processing. The full-width half maximum (FWHM) of the cross-sections was determined and found to be similar for the two systems (4.3 mm with the Focused Ultrasound Foundation [FUSF] system, 4.4 mm with the commercial systems).

The radial cross-section through the focus was compared with an O'Neil pressure simulation (Fig. 3). The simulation parameters were 350-kHz frequency, 22-mm transducer radius, 31.5-mm radius of curvature for the focused transducer. The pressure is reported in arbitrary units, normalized to the maximum pressure. Excellent agreement was found between the measured and theoretical widths of the main lobe and the side lobes' locations.

Pressure measurements for a plane transducer

Both hydrophone scanners were used to measure a 1.1-MHz, 11-mm-diameter plane transducer through the natural focus at 23 mm. The last axial pressure maximum for a plane transducer occurs at the distance that serpates the near and far fields of a plane transducer, and is called the natural focus (Szabo 2004). In addition, the pressure field was simulated using the hybrid angular spectrum (HAS) method. Figure 4 illustrates the results of the scans and simulation. The hydrophone scanners recorded similar results qualitatively. The recorded peak negative pressures varied by only 8.9% between the two systems. The FWHM of both scans was calculated with a 13.0% difference (Table 2). The HAS pressure amplitude was normalized to the maximum peak pressure in the FUSF scan. The FUSF scan has a diameter similar to that of the HAS simulation, although the rings are less noticeable. This could be owing to low signal-to-noise

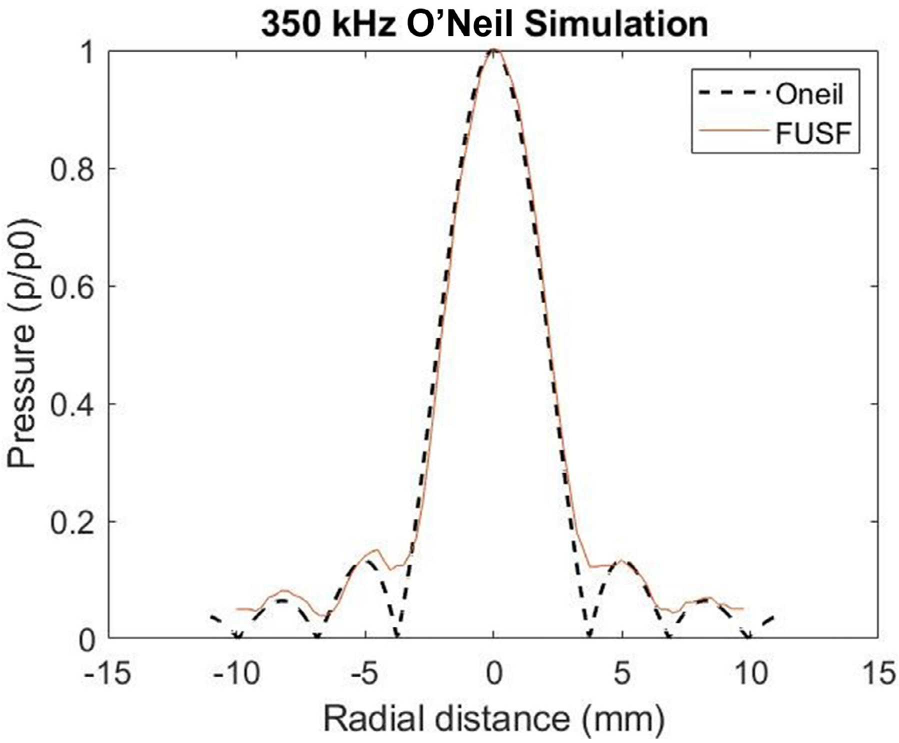

Fig. 3. Focused Ultrasound Foundation (FUSF) low-cost model radial scan of 350-kHz circle transducer compared with focused circular transducer pressure simulation.

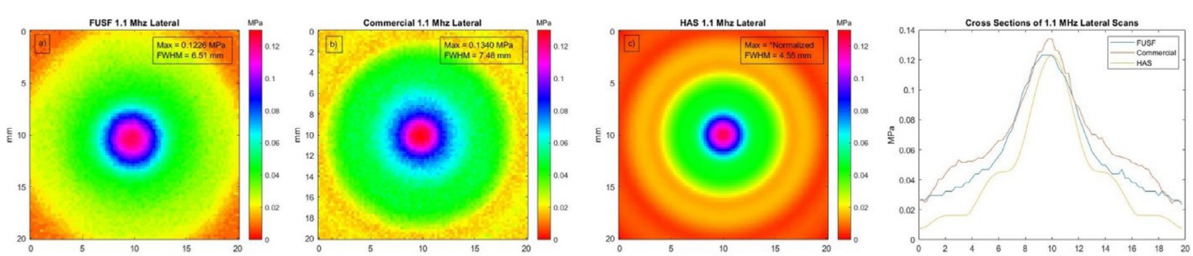

Fig. 4. Side-by-side comparison of transverse 20 × 20-mm 0.25-mm-resolution negative pressure (MPa) scans of 1.1-MHz plane transducer with (a) Focused Ultrasound Foundation (FUSF) low-cost model, (b) commercial model and (c) hybrid angular spectrum (HAS) simulation. Right: Horizontal cross section through maximum pixel value of lateral scans. The experimental scans are similar in peak pressure and lobe width. The HAS simulation is similar if accounting for experimental error.

Table 2. Comparison of maximum peak negative pressure and FWHM of cross-sections from

	FUSF	Commercial	% Difference	HAS	% Difference
xy Maximum peak negative pressure (MPa)	0.1226	0.1340	8.9%	n/a	n/a
xy Cross-section FWHM (mm)	6.51	7.48	13.0%	4.55	35.4%

ratio away from the main lobe in the hydrophone measurements.

The FWHM of the simulation was smaller compared with both the FUSF and commercial scans. Experimental error in the FUSF and commercial scans can explain this difference. The hydrophone may have been positioned away from the natural focus at 23 mm as the pressure gradient in the axial direction is relatively uniform here. We reduced this error manually by finding the time of flight for each scan; however, the

Table 3. Low standard deviation reveals repeatability between scans on FUSF low-cost model Values are given as average ± standard deviation.

	350 kHz	1.1 MHz
xy Maximum peak negative pressure (MPa)	0.239 ± 0.0045	0.124 ± 0.0012
xy Cross section FWHM (mm)	4.293 ± 0.0298	6.408 ± 0.0928

FWHM = full width half-maximum; FUSF = Focused Ultrasound Foundation.

Table 4. Low-cost hydrophone scanner position repeatability measurements

Scan displacement (mm)	x-Axis (μm)	y-Axis (μm)	z-Axis (μm)
0.250	−2.3 ± 10.3	−0.2±10.3	2.0 ± 10.7
1	1.0 ± 28.0	7.5 ± 12.2	3.1 ± 11.0
20	39.4 ± 73.5	36.117 ± 58.4	3.393 ± 98.4

MATLAB software does not do this automatically. The simulation assumed a speed of sound in water of 1500 m/s, which neglects temperature variations. Furthermore, Figure 4 illustrates the cross sections for both scans and the simulation. These plots suggest the experimental FWHM could be influenced by noise, which has an averaging effect on the scan's cross-section. The noise obscures the lobes, and the main lobe becomes less sharp. These compounding experimental errors explain the larger experimental FWHM. However, notably the FUSF and commercial transverse images have similar results.

Reproducibility of the low-cost scanning tank

To illustrate the low-cost scanning tank's repeatability, five transverse images of both the 350-kHz focused and the 1.1-MHz plane transducers were acquired, with the scanner reset after taking each scan. The low standard deviation of the maximum negative pressure and FWHM reflects the device's ability to consistently find the focal point and natural focus (Table 3). The corresponding coefficients of variation for both transducers are less than 2% (1.88% for the 350-kHz transducer and 0.98% for the 1.1-MHz transducer). This variance is in line with the reported intra-hydrophone repeatability of 0.4% to 2%. Martin and Treeby (2019) found larger variations for needle hydrophones caused by misalignment with the beam, which is likely a significant source of variation for this study. However, the comparable variance indicates that the low-cost scanner can repeatably align and acquire the hydrophone signal within the variance of other automated hydrophone scanners (Martin and Treeby 2019).

We performed measurements to assess the reproducibility and precision in positioning the low-cost scanner, using a step size of 0.25 mm. In place of the hydrophone, a webcam imaging apparatus attached to the scanner recorded the precise displacement from a microscope calibration ruler for each axis from the point of origin. This process yielded precise measurements describing the system's ability to reposition after a scan. Results revealed the positional accuracy and repeatability for all axis displacements were below 120 μm, even after a 20-mm scan with 250-μm step size (Table 4). After scanning over a 20-mm length in any direction, the average error in positioning was less than 50 μm.

Convergence of the low-cost scanning tank

To test the convergence of the low-cost transducer, we performed 2-D scan acquisitions near the focus of the 350-kHz transducer, with various step sizes of 0.1, 0.25

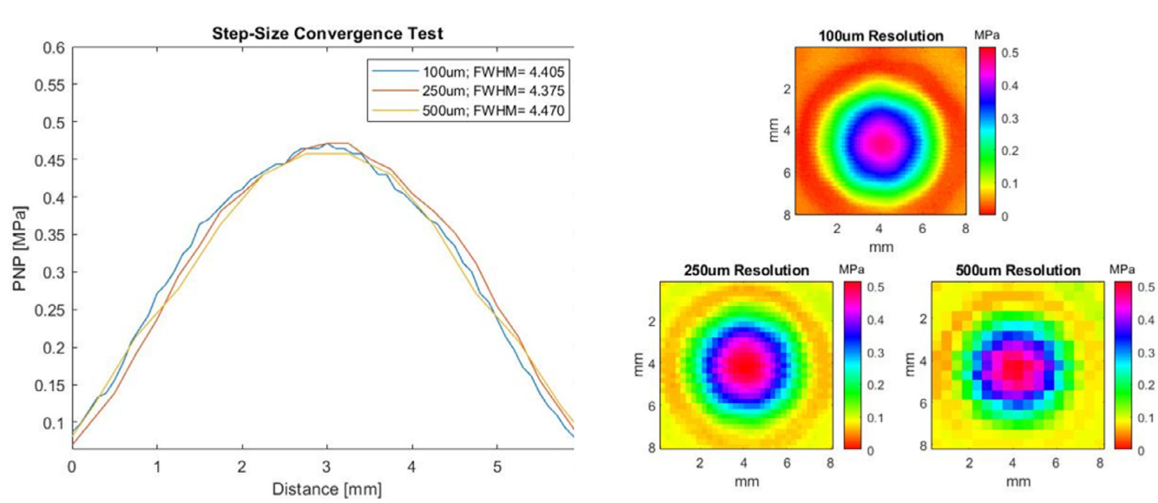

Fig. 5. Left: Pressure profiles near the focus of the 350-kHz transducer after scanning with a step size of 0.1, 0.25 or 0.5 mm. Right: Corresponding 2-D scans at focus. PNP = peak negative pressure.

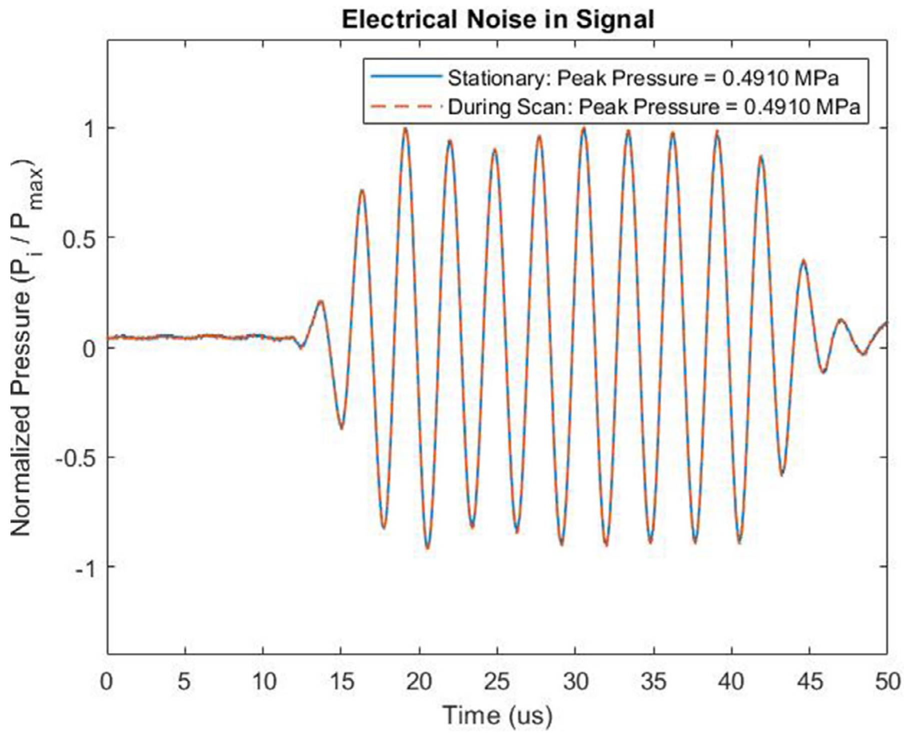

Fig. 6. Signal acquisitions at focus with motors turned on (*dashed orange line*) and off (*blue line*). There is negligible electrical noise caused by motors and drivers.

and 0.5 mm. The FWHM was very similar for the three step sizes (4.40, 4.37 and 4.37 mm for the 0.1-, 0.25- and 0.5-mm step sizes, respectively) (Fig. 5). Similarly, the peak pressure at the focus was also very similar for the three scans (0.47 $\pm$ 0.008 MPa). This convergence test confirms that the 0.25-mm step size used for the analyses of the low-cost scanner was valid.

Electrical noise of low-cost scanning tank

We acquired signals at the focus of the 350-kHz transducer, with motors turned on and off (Fig. 6). No noticeable difference in the signal's amplitude could be detected, suggesting that the noise produced by the stepper motors and drivers is negligible.

DISCUSSION AND CONCLUSIONS

With only moderately longer scan times than with a commercial system, and likely there is room still to improve scan times, the low-cost scanning system proposed here exhibited excellent reproducibility and an error of only 3.2% in measured pressure values compared with data acquired with a commercial system. Many improvements could be made to expand on the basic functionality described here. The scanning software, which is programmed for a Tektronix Oscilloscope, could be modified to use a PicoScope. Then each lab could use the same affordable oscilloscope, reducing the time needed to modify the MATLAB GUI for each lab's available equipment. Another improvement could be made in automated signal processing. The GUI can currently save the waveform for each location, enabling post-processing. Automated signal processing could find a phasor for each location, which contains the relative phase and magnitude. From these data, a 2-D scan may be propagated into three dimensions using the angular spectrum. The proposed low-cost scanning system developed here is a viable solution for ultrasound labs needing efficient, low-cost spatial quantification of ultrasound transducers.

The FUS Foundation has made available instructions and software to build and control one's own hydrophone scanning tank using 3-D printing and sourced parts for a total cost of about $1000. With its robust design, this low-cost 3-D hydrophone scanning tank is an open-source alternative to commercial systems.

Conflict of interest disclosure—The authors declare no commercial or financial conflict of interest.

SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.ultrasmedbio.2021.09.022.

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