A High Frequency Ultrasound Actuated Synthetic-Aperture Array.

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Abstract – An Actuated Synthetic-Aperture Array (ASA) system is described that is capable of overcoming the technical difficulties in manufacturing an ultrasonic phased array in the 30 to 70 MHz frequency range. The system is capable of generating images using a linear array of transducers which are of equal quality compared to a 64-element phased array while. The array was rapidly and precisely positioned with a piezoelectric actuator. The image was formed utilizing a synthetic aperture (SA) approach rather than electronic beamforming. The SA image was further refined by application of a deconvolution algorithm.

Keywords – High Frequency Ultrasound, Synthetic Aperture Reconstruction, Actuated Synthetic Aperture Array.

I. INTRODUCTION

Ultrasound transducers that operate at frequencies from 30 to 70 MHz are required to obtain the resolution needed for ultrasonic imaging of the eye, blood vessels and skin [1]. There are currently two main challenges to building such devices. The first is the difficulty in constructing array elements with very small feature sizes needed for good acoustic operation at such high frequencies. The second is the difficulty and expense of constructing a high frequency beam former.

To solve these problems a precision piezoelectric actuator mechanically scanned a linear array, spatially sampling in $\lambda/4$ steps between each element. An image was formed from the RF data lines using synthetic aperture reconstruction. This Actuated Synthetic-aperture Array (ASA) system employed a 12-element 50MHz linear array to generate images of quality very similar to what one would expect from a 64-element phased array operating at the same frequency [2]. In addition, since a synthetic aperture approach was used, only one channel was required as opposed to 64 channels, including RF electronics and beamformer, required for a 64 element phased array. Array performance was demonstrated with actual images of 20 µm-wire phantoms, and the measured lateral image resolution was found to be 22 µm. Figure 1 is a block diagram showing the major components of the ASA system (described in section II).

High frequency ultrasound is beneficial to both ophthalmology for imaging the anterior region of the eye, in dermatology for melanoma screening and metastasis detection [1, 3]. The routine use of high frequency ultrasound screening in doctors’ offices would provide immediate benefits include preventing blindness and saving lives of cancer victims. However, this also means that the ultrasound systems must be relatively inexpensive, precluding the use of complex beam forming electronics[4, 5]. The ASA transducer is an effective solution to this problem.

![Fig. 1 Block diagram of the ASA system.](image)
sophisticated method using multiple channels and multistatic acquisition could also be employed.

II. METHODOLOGY

A. ASA Transducer

The transducer used in the experiments was a 12 element array that was designed and constructed at Penn State [2]. The transducer was fabricated by the stacked plate technique with element pitch of 105 µm and element width of 80 µm was used to perform ASA imaging experiments at frequencies near 50 MHz. The transducer was encapsulated in a waterproof housing, characterized for pulse-echo properties and bandwidth, and attached to the positioning system.

B. ASA Architecture

The system electronics and controls that interface to the array are depicted in Figure’s 1 and 2 and Table 1 is a list of the major components. Figure 1 is a block diagram of the system and Figure 2 is a photograph of the positioning system, transducer, and tank. The system consists of the following subsections: an analog RF section which is comprised of a Panametrics 5900 Pulser-Receiver unit, a motion control section which consists of a 3-axis positioning system composed of three orthogonal Velmex UniSlide’s with associated stepper motors controlled by a National Instruments PCI-7344 4-axis controller card, a Physik Instruments Piezo-Ceramic actuator with feedback control system, a Stanford Research Systems (SRS) Model DG535 digital delay generator, and finally a multi-processor workstation that houses a Gage 82G 1 GHz A/D card with 8MB of onboard memory. The RF subsystem noise floor was analyzed and the subsystem was interfaced to the high speed data acquisition system. Software control architecture was designed, written, and tested for position system scanning, data acquisition, filtering and noise removal, synthetic aperture focusing, and image formation.

The basic operation of the controller architecture is the following: upon initialization the controller will perform 14 Actuator Steps of 7.5 microns to cover a range of 105 microns which is equivalent to the pitch of the array. For an actual full-scale array, at each step of the actuator all 30 elements of the array would be pulsed and accessed which takes approximately 483 microseconds and approximately 443 kB of data assuming a sampling rate of 1 GHz. This process is illustrated schematically in Figure 3. This requires a multiplexer for a monostatic approach and a full 30 channels for multistatic acquisition. Thus to prove feasibility only one element of the array was used.

<table>
<thead>
<tr>
<th>Device</th>
<th>Manufacturer</th>
<th>Model</th>
</tr>
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<tbody>
<tr>
<td>Piezoelectric Actuator</td>
<td>Physik Instruments</td>
<td>PZT</td>
</tr>
<tr>
<td>Screw-driven Actuator</td>
<td>Velmex</td>
<td>A-15</td>
</tr>
<tr>
<td>Stepper Motor</td>
<td>Oriental Motor</td>
<td>RFK545A</td>
</tr>
<tr>
<td>Motion Controller &amp; DIO</td>
<td>National Instruments</td>
<td>7344</td>
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<td>ADC</td>
<td>Gage Instruments</td>
<td>CS82G</td>
</tr>
<tr>
<td>Ultrasound Pulser/Receiver</td>
<td>Panametrics</td>
<td>5900PR</td>
</tr>
<tr>
<td>Delay Generator</td>
<td>Stanford Research System</td>
<td>DG535</td>
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</table>
This process was repeated 30 times to simulate the input from a full 30 element transducer for the synthetic aperture software. Note that the actuator control parameters (the number of steps and the step distance) were determined assuming a center frequency of 50 MHz; however, the actual transducer center frequency was 43 MHz. This will probably introduce a small amount of error in the synthetic aperture image reconstruction. The reconstruction was done using the actual center frequency but this does not correlate to the actuator step size. These types of errors will be analyzed more thoroughly in future work.

The piezoelectric actuator used for the experiment had a total travel range of 120 \( \mu \text{m} \) and a closed loop displacement resolution of 2.4 nm. Feedback servo control was based on the output of a strain gauge integrated into the actuator package.

All positioning and data acquisition were controlled by a C-code program running under Microsoft Windows 2000 on a Dell Precision 530 workstation (PC). The positioning of the ultrasound transducer (UT) involves a two stage process. The first stage is a coarse positioning of the UT to the starting location by a screw-driven actuator which is powered by the PC controlled stepper motor. Upon completion of the coarse movement, the program moves the UT in a series of rapid and precise 7.5 micron steps by controlling a piezoelectric actuator which is powered by the PC controlled stepper motor.

Upon completion of the coarse movement, the program moves the UT in a series of rapid and precise 7.5 micron steps by controlling a piezoelectric actuator. Following each 7.5-micron step, the program enables the analog-to-digital converter (ADC) to capture a scanline, triggers the pulsing of the UT, waits for the completion of the data capture, and transfers the recorded RF signal from the ADC to the corresponding row within a data matrix. Upon completion of the fourteen 7.5-micron steps the piezoelectric actuator is returned to the starting position and the screw-driven actuator moves forward 105-microns and the piezoelectric actuator loop repeats. After the final piezoelectric actuator loop completes and piezoelectric actuator is returned to the initial position, the screw-driven actuator is returned to its home position and the scanline data are written to a file.

The future version of the system will contain a multiplexer that will sequentially select each of thirty elements of the transducer array. At each 7.5-micron step of the piezoelectric actuator a scanline will be recorded from each of the 30 elements of the array.

C. Synthetic Aperture Image Reconstruction

Synthetic aperture processing for ultrasound imaging is described by numerous authors. Image reconstruction can be accomplished in the time-domain using a backprojection technique. The reconstruction method is described using an array of elements \( e_i \) through \( e_N \), where a single point target is located at coordinate \( x_e, z_e \) in object space. If each element is used as a separate transmitter-receiver pair, the response for each element is simply the pulse reflected by the point target. Assuming omni-directional response, the reflected pulses recorded for the elements will be identical in amplitude and shape but shifted in time according to the distance from the element to the point.

Backprojection is accomplished by summing contributions to each pixel in the time domain according to the relationship:

\[
P(x_i, z_i) = \sum_{e=1}^{e=N} w_e R_e \left[ \frac{2}{c} \sqrt{(x_e - x_o)^2 + z_e^2} \right]
\]

where \( x_{o}, z_{o} \) is the pixel location in image space, \( w_e \) is the apodization, \( R_e \) is the time-domain response, \( t \) is the time, \( c \) is the propagation velocity, and \( x_e \) is the element position. One data point from each RF line contributes to each pixel in the beamformed image. From the perspective of a lone element, the actual position of the point is determined in terms of the "arc" over which the point reflector may be located. This concept is shown in Figure 4 for six array elements, where each element has a corresponding arc. The arcs from each element will overlap in only one point, the actual position of the reflector. In some sense this process resembles a form of triangulation. By using many elements and forming a coherent sum, it is possible to map the entire image with minimal ambiguities.

![Figure 4 – Synthetic aperture reconstruction](image)

D. Deconvolution

The deconvolution procedure that was applied to the SA image used a maximum likelihood algorithm [6, 7]. The algorithm selected was the Lucy-Richardson procedure which assumes Poisson noise statistics while maximizing the likelihood that the deconvoluted image is an instance of the blurred image. The estimates of the point spread function
(PSF) for each of three wire-depth locations were obtained from the SA images of the actual wire phantom.

II. RESULTS

The initial image that was generated by the synthetic aperture (SA) algorithm had room for improvement in lateral resolution (Figure 10a). Ideally, each of the three 20-micron wires should appear as a three-by-three pixel box in the resulting image. To reduce the lateral blurring of the wire images, an image processing stage was included to deconvolute the point spread function (PSF) that was associated with each of the wires. Since the PSF’s were depth dependent, an estimate was obtained from the SA image for the wires at each depth location.

Figure 6 (left side) shows –6dB reconstructed images of the wire phantom using the monostatic synthetic aperture algorithm under a half reconstruction angle of 19º. The tested ASA image is very close to the simulated image demonstrating the ASA imaging concept. The right side of Fig. 6 shows the deconvolution image of the –6dB ASA reconstruction using the Lucy-Richardson algorithm. A clear point spread function was obtained (right hand side of the figure), and the transverse resolution of the ASA imaging was then obtained by investigating the lateral point spread functions for the three wire phantoms. The transverse resolutions were 22, 37, and 38 µm for the wires at depths of 3, 6, and 9 mm, respectively. This is an extremely exciting result and clearly demonstrates the feasibility of the ASA concept.

III. Conclusion

The feasibility of the ASA transducer concept was clearly demonstrated. Wire phantoms 20 µm in diameter were imaged at 43 MHz with a transverse resolution of 22 µm. This is better than simulated phased array results [8]. Thus, precision mechanical scanning can be combined with a coarse array and synthetic aperture software to create a hybrid transducer concept that can solve the daunting problems of high frequency array transducers.

ACKNOWLEDGMENT

Funding for this work was provided by National Institutes of Health through a Phase I SBIR.

REFERENCES