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Automated Characterization of Matrix Transducer Arrays using the Verasonics Imaging System

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Abstract—**Over the past decades, ultrasound imaging has made considerable progress based on the advancement of imaging systems as well as transducer technology. With the need for advanced transducer arrays with complex designs and technical requirements, there is also a need for suitable tools to characterize such transducers. However, despite the importance of acoustic characterization to assess the performance of novel transducer arrays, the characterization process of highly complex transducers might involve various manual steps, which are laborious, time-consuming, and subject to errors. These factors can hinder the full characterization of a prototype transducer, leading to an under-representation or inadequate evaluation. To come to an extensive, high-quality evaluation of a prototype transducer, the acoustic characterization of each transducer element is indispensable in both transmit and receive operations. In this paper, we propose a pipeline to automatically perform the acoustic characterization of a matrix transducer using a research imaging system. The performance of the pipeline is tested on a prototype matrix transducer consisting of 960 elements. The results show that the proposed pipeline is capable of performing the complete acoustic characterization of a high-element count transducer in a fast and convenient way.**

Keywords—ultrasound transducer, matrix array, automated, acoustic characterization, Verasonics, research imaging system.

I. INTRODUCTION

Over the past decades, ultrasound imaging has made considerable progress. Novel approaches and breakthroughs in diagnostic and therapeutic ultrasound together with the continuous improvement in electronics have prompted quick and significant advancements in imaging systems and transducer technology [1], [2]. With the need for cutting-edge transducer arrays with complex designs and ambitious technical requirements (e.g., reduced size, increased number of elements, improved sensitivity, and wide bandwidth), there is also a need for suitable tools to characterize, test, and evaluate such transducers [3].

The acoustic characterization is a crucial process in the design of ultrasound transducer arrays [4], [5]. This process is necessary to validate models, analyze variations between transducer elements, evaluate the manufacturing process, and investigate various acoustic phenomena that influence the transducer's behavior in practice [6], [7]. Thus, to develop new and better probes, it is very important to have a good knowledge of the performance of the prototyped transducers experimentally [8].

Another essential role of acoustic characterization is to provide means for the maintenance of transducers available for clinical use. It is well known that the operating characteristics of an ultrasound transducer tend to change with time and usage with an average life expectancy, which is sometimes limited to a few months of continuous use. Besides, the transducer might suffer from severe degradation depending on the environment [3]. These aspects might raise concerns with regard to the effectiveness and safety of the transducer for a specific clinical application [9]. Therefore, test routines must be established to periodically evaluate the performance/operation of medical transducers and to check their conformance with national and international standards [10].

Despite the importance of the acoustic characterization process and the great advances in transducer technology, little has been reported on describing the setup needed for the characterization of these novel transducers. Without appropriate tools, the characterization process of highly complex prototype transducers might involve various manual steps, which can be laborious, time-consuming, and subject to errors [11]. This might discourage a complete characterization of the transducer (especially if it has a large number of elements) leading to an under-representation or inadequate evaluation of the prototype (e.g., assessing the performance of the transducer only in terms of a pulse-echo test [12]). To come to an extensive, high-quality evaluation of a prototype transducer, an element-level characterization of both transmit and receive operations is indispensable. In this paper, we present a pipeline to automatically perform the acoustic characterization of each individual element of a matrix transducer using a research imaging system. The performance of the proposed pipeline is tested on a prototype matrix transducer consisting of 960 elements.

II. AUTOMATED ACOUSTIC CHARACTERIZATION

The experimental setup for the automated characterization of the prototype transducer is schematized in Fig. 1. As seen, multiple instrumentation devices are integrated to perform different measurement tasks, which are controlled and synchronized by the host computer of the Verasonics imaging system (V1, Verasonics, Inc., Kirkland, WA, USA) via MATLAB interface (2014b, The MathWorks, Inc., Natick, MA, USA) using external functions. The proposed pipeline can be divided into three main parts:

A. *Alignment procedure*

The alignment procedure is used to align the prototype transducer with a needle hydrophone prior to the transmit characterization. This is required to reduce the influence of the hydrophone directivity in the measurements. The flowchart of the procedure is shown in Fig. 2. First, the user

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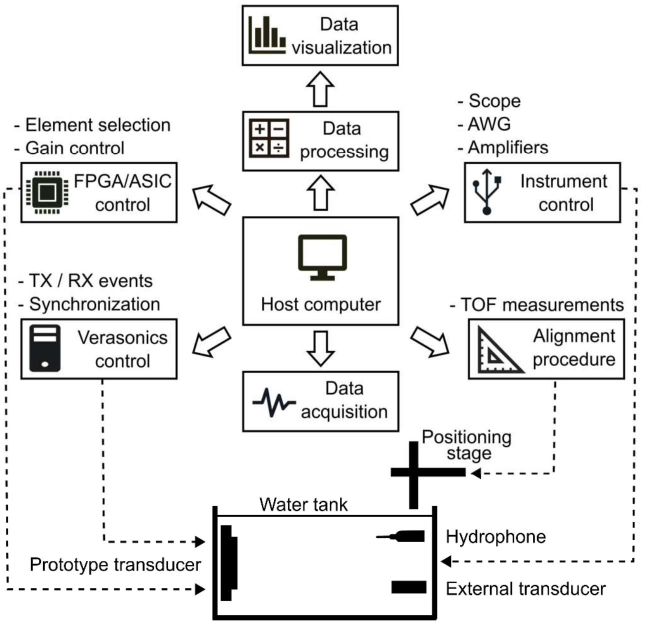

Fig. 1. Experimental setup for the automated characterization.

selects the element to be aligned with the hydrophone and defines the acquisition settings. Then, the Verasonics (indicated as "VSX" in the flowchart) drives a group of elements individually and sends a trigger to the oscilloscope ("Scope"). For each transmit event, the hydrophone signal is digitized by the oscilloscope and transferred to the computer. Next, the time-of-flight (TOF) of the hydrophone signal is measured and used to estimate the relative distance between the hydrophone and the element under alignment. Finally, the calculated coordinates are sent to the *xyz*-positioning stage to move the hydrophone to the aligned position. The performance of the alignment procedure is displayed to the user in real time for evaluation.

B. *Transmit characterization*

The flowchart of the transmit (TX) characterization is shown in Fig. 3. The process starts with the acquisition settings defined by the user. Then, the Verasonics drives the transducer elements individually. For each transmit event, the hydrophone signal is digitized by the oscilloscope and transferred to the computer, where data is processed and displayed in real time. When the acquisition is complete, the user can visualize the variation in transmit efficiency across the transducer elements, as well as the time and frequency response parameters of all individual elements. Furthermore, this setup can be utilized to measure the directivity pattern of individual elements. For this, the hydrophone is automatically rotated between the transmit events.

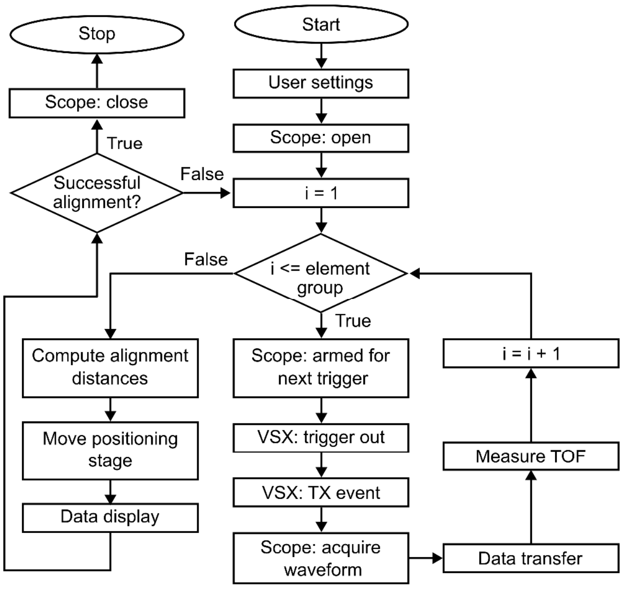

Fig. 2. Flowchart of the alignment procedure.

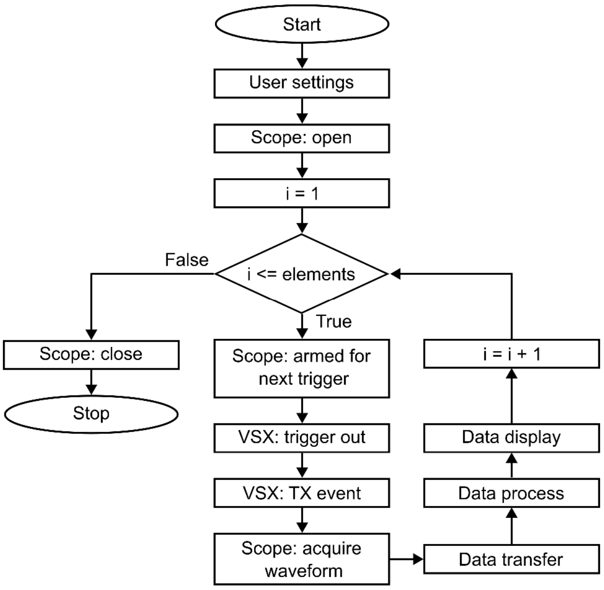

Fig. 3. Flowchart of the automated transmit characterization.

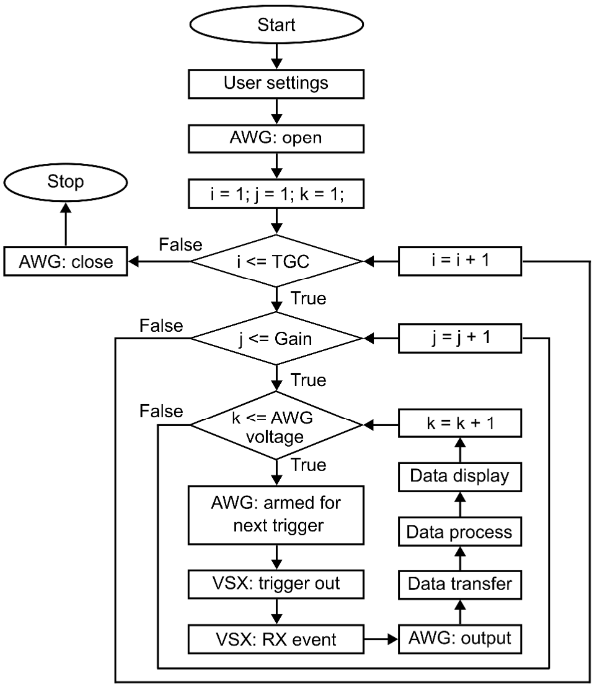

Fig. 4. Flowchart of the automated receive characterization.

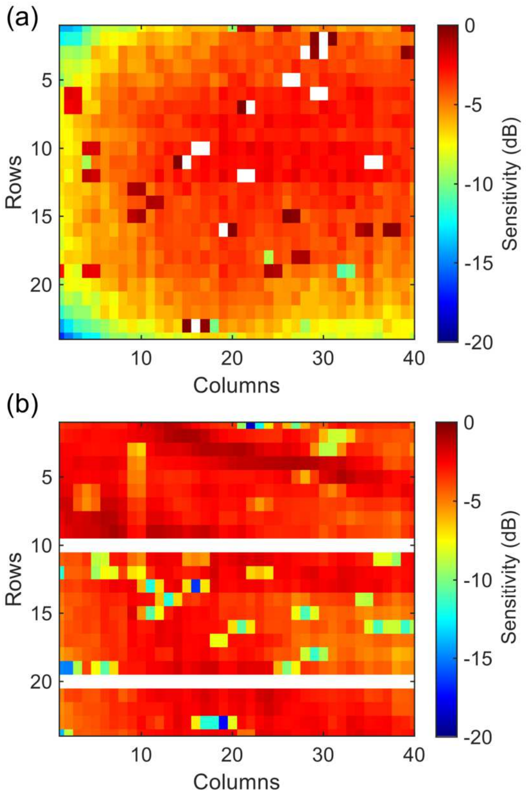

Fig. 5. (a) Transmit efficiency. (b) Receive sensitivity. The elements shown in white are faulty.

C. *Receive characterization*

The flowchart of the receive (RX) characterization is shown in Fig. 4. For this process, a pre-calibrated external transducer is used as a transmitter. First, the user defines the receive gain settings, which include the prototype in-probe amplifiers (indicated as "Gain" in the flowchart) and the Verasonics time-gain compensation (TGC). The user also selects the voltage range of the arbitrary waveform generator (AWG) to drive the external transducer. Next, the Verasonics sweeps through the range of gains and output voltages. For each iteration, the received signal of individual elements is recorded and the variation in receive sensitivity across all elements is displayed in real-time. When the acquisition is complete, the overall dynamic range (i.e., the relationship between received acoustic pressure and output voltage) is displayed to the user.

III. PROTOTYPE MATRIX TRANSDUCER

We have fabricated a prototype matrix transducer array made of lead zirconate titanate (PZT) that operates at 7.5 MHz and consists of 960 elements with a pitch of 300 µm × 150 µm. The PZT matrix was mounted on top of an application-specific integrated circuit (ASIC) whose element-level circuits match the pitch of the array. The prototype transducer interfaces with the Verasonics imaging system using a custom-designed printed circuit board (PCB). More details about the design of the prototype transducer can be found in our previous publications [13]–[15].

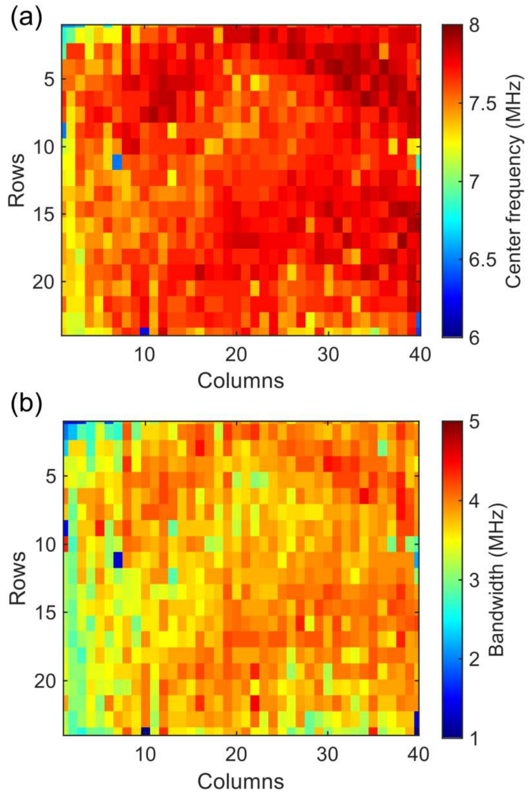

Fig. 6. (a) Center frequency. (b) Bandwidth $_{-6\ \text{dB}}$.

IV. RESULTS AND DISCUSSION

Fig. 5(a) and Fig. 5(b) show the sensitivity variation across all elements of the prototype transducer obtained from the automated transmit and receive characterization, respectively. As seen, the majority of the elements are working within the 0 dB to -6 dB level in both transmit and receive. Note however that rows 10 and 20 are defective in receive.

After the alignment procedure, the transmit sensitivity characterization takes about 10 minutes to be carried out. This means that, for each element, it takes approximately 0.6 seconds for the acquisition of the hydrophone signal, data transfer, and processing. The receive sensitivity characterization of the entire prototype is much quicker: it is complete in just a few seconds. However, note that the alignment procedure for the receive characterization is not yet automated. Currently, the real-time sensitivity map, as

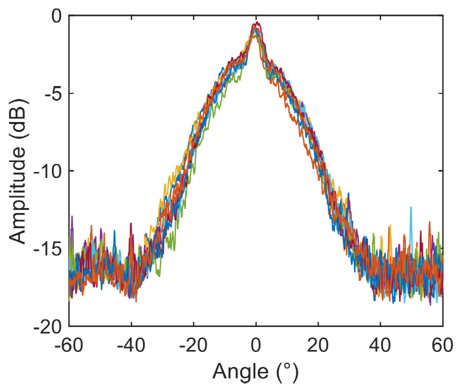

Fig. 7. Directivity pattern of a few elements.

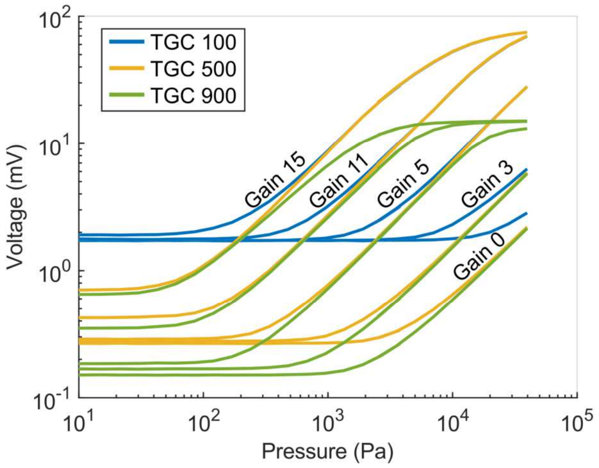

Fig. 8. Relation between the received pressure at the transducer surface and the corresponding output voltage for different gain settings.

the one shown in Fig. 5(b), is used as a guide for the alignment (i.e., the user manually finds the position of maximum acoustic pressure from the external transducer).

The center frequency and -6 dB bandwidth derived from the transmit characterization are shown in Fig. 6(a) and Fig. 6(b), respectively. Most of the elements exhibit a center frequency between 7.5 and 8 MHz, in accordance with the acoustic design. The majority of the elements show a bandwidth of around 3.5 MHz, which represents approximately 45%.

Fig. 7 shows the directivity pattern in transmit for nine arbitrarily selected elements. As seen, all elements exhibit a -6 dB beam width of about 32 degrees and a sharp peak at 0 degrees (we believe that this bump is due to electrical crosstalk, but further investigation is needed). At the beginning of each set of scans, the hydrophone was automatically aligned with the selected element. Since a very good agreement is observed between the different elements, we can imply that the alignment procedure was successfully performed with low variability. The alignment procedure takes about 2 minutes to be conducted.

Fig. 8 shows the relation between the received pressure at the transducer surface and the corresponding output voltage for different gain settings. The plotted values represent the average over the 960 transducer elements. The minimum detectable pressure is about 60 Pa, whereas the maximum measured pressure is about 40 kPa. Thus, the measured dynamic range is 56 dB. The dynamic range characterization takes about 15 minutes to be carried out.

V. CONCLUSIONS

In this paper, a pipeline for the automated acoustic characterization of an ultrasound matrix transducer is presented. The implemented workflow, which is controlled by the host computer of the Verasonics imaging system, consists of an alignment procedure based on TOF measurements, followed by the transmit characterization with a hydrophone, and the receive characterization for different gain settings using an external transducer. The performance of the pipeline was evaluated on a prototype PZT matrix transducer consisting of 960 elements. The results demonstrate that the proposed pipeline can be used as a rapid and convenient method to perform the element-level characterization of a matrix transducer. Compared to manual characterization, the proposed pipeline can significantly enhance the quality of the characterization process of prototype transducers and hence lead to an improved probe design. Future work will include a process to measure the acoustic crosstalk between the transducer elements.

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