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Full Volumetric 3-D Vector Flow Imaging using a 62+62 Row-Column Array

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Abstract—Row Column (RC) Arrays can produce high-resolution 3-D volumetric images with only 2N interconnections compared to N^2 for matrix probes. A 62+62 RC probe has four times larger surface area and one-eighth of the channel count when compared to the same-pitch fully populated 32x32 matrix probe. This research investigates the performance of such a prototype array for volumetric Synthetic Aperture (SA) B-mode and vector flow imaging using defocused waves. An interleaved SA sequence was implemented on the SARUS scanner using a 3 MHz, λ/2-pitch 62+62 RC piezoelectric probe. The sequence contains repeated emissions with rows and columns interleaved with B-mode emissions. The sequence contains 80 emissions in total and can provide a volume rate above 125 Hz yielding continuous data. Velocities were estimated using the Directional Transverse Oscillation Cross-Correlation method. Measurements were made on a circulating flow rig with a parabolic profile with a peak velocity of 0.25 m/s and beam-to-flow angle of 90° were made on a circulating flow rig with a parabolic profile with a peak velocity of 0.25 m/s and beam-to-flow angle of 90°. Transverse Oscillation Cross-Correlation method. Measurements were made on a circulating flow rig with a parabolic profile with a peak velocity of 0.25 m/s and beam-to-flow angle of 90°. The sequence contains 80 emissions in total and can provide a volume rate above 125 Hz yielding continuous data. Velocities were estimated using the Directional Transverse Oscillation Cross-Correlation method. Measurements were made on a circulating flow rig with a parabolic profile with a peak velocity of 0.25 m/s and beam-to-flow angle of 90°. The sequence contains 80 emissions in total and can provide a volume rate above 125 Hz yielding continuous data. Velocities were estimated using the Directional Transverse Oscillation Cross-Correlation method. Measurements were made on a circulating flow rig with a parabolic profile with a peak velocity of 0.25 m/s and beam-to-flow angle of 90°. The sequence contains 80 emissions in total and can provide a volume rate above 125 Hz yielding continuous data.

II. METHODS

A. Imaging Sequence and Beamforming

A 62+62 RC piezoelectric experimental probe [14] was connected to the research scanner SARUS [15]. This allowed full control over emissions and storing of all channel data. Using SA, each emission can be beamformed to reveal a low resolution volume (LRV). A single LRV will reveal a volume only focused in receive. However, summing multiple LRVs with changing transmit geometries (virtual line sources) will reveal a high resolution volume (HRV) [16]. HRVs are then focused dynamically both in receive and synthetically in transmit. The SA sequence used here interleaves the flow emissions inside a flow block, and it also interleaves B-mode emissions between flow blocks. The sequence uses a combination of row emissions (R) and column emissions (C) suited for flow estimation, see section II-B for details.

B-mode requires a higher number and more widespread virtual lines sources to avoid grating lobes and limit the side-lobe energy to improve contrast. The B-mode emissions were therefore interleaved, with 4 emissions per block, in between flow blocks in the following pattern:

\[ \begin{array}{cccc}
R(16) & B_R(4) & C(16) & B_R(4) \\
R(16) & B_R(4) & C(16) & B_R(4) \\
\end{array} \]  

(1)

Here \( B_R \) indicates that the emissions are used for B-mode and that the emissions are performed with rows. The number in parentheses correspond to the number of emissions in each block. \( R \) and \( C \) symbolize flow blocks. \( R \) have rows as transmitting elements and columns elements are receiving. \( C \) is the flipped setup, having columns as transmitting elements.
A single flow block, here using $R$ as an example, generated a total of two HRVs ($HRV_a, HRV_b$). Each HRV is synthesized from eight LRVs, with different transmit virtual line sources. The emissions were defocused to ensure high spatial overlap of the emitted waves in front of the transducer. This was employed by placing the virtual line sources behind the transducer. A sliding aperture approach using 32 active line sources. The emissions were defocused to ensure high spatial overlap of the emitted waves in front of the transducer.

**TABLE I**

**PROBE PARAMETERS AND IMAGING SETTINGS**

<table>
<thead>
<tr>
<th>Probe dimensions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements</td>
<td>62+62</td>
</tr>
<tr>
<td>Center frequency:</td>
<td>3 MHz</td>
</tr>
<tr>
<td>Kerf</td>
<td>25 µm</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.27 mm</td>
</tr>
<tr>
<td>Element length</td>
<td>19 mm</td>
</tr>
<tr>
<td>Total Surface area</td>
<td>280.23 mm²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Imaging Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Apodization</td>
<td>Hann</td>
</tr>
<tr>
<td>F# (TX/RCV)</td>
<td>-1/1</td>
</tr>
<tr>
<td>Number of active elements</td>
<td>32</td>
</tr>
<tr>
<td>No. transmitted cycles</td>
<td>2</td>
</tr>
<tr>
<td>Transmit frequency</td>
<td>3 MHz</td>
</tr>
<tr>
<td>$f_{prf}$</td>
<td>2 kHz</td>
</tr>
</tbody>
</table>

and rows as receivers. This way, only 62 channels have to be active in receive per emission. This reduces the bandwidth, data handling, and hardware requirement.

**B. Velocity Estimation**

The TO method requires an oscillating field in the transverse direction to estimate the velocity component parallel to the transducer surface. This was employed using a dual peak apodization in receive as visualized in Fig. 1. The field will only be oscillating in one direction e.g. in x, in this case. This is why only $v_x$ can be estimated when rows are emitting. $v_y$ is estimated using block $C$. $v_z$ can be estimated in either case due to the natural oscillation of the propagating wave. Velocities were estimated using Directional Transverse Oscillation (DTO) [18]. Interleaving flow emissions have already shown to provide higher detectable velocities and better performance in 2-D SA flow estimation [12], [13]. The approach is not limited to 2-D and can be employed on a full volume at once and provide full 3-D volumetric estimates.

**C. Experimental Setup**

Two phantom setups were used. A constant flow setup for validation (setup 1) and a tissue-mimicking phantom with pulsating flow (setup 2). Setup 1 was a rubber tube with a radius (R) of 6 mm submerged in water and blood mimicking fluid was flowing inside the tube driven by a pump. A MAG 1100 flow meter (Danfoss, Hasselager, Denmark) was attached to measure the volume flow rate $Q$, and determine the reference flow profile [7]. Assuming parabolic flow and a beam-to-flow angle of 90 degrees, the true center profile is:

$$v(\phi)(r) = \{v(r) \cdot \cos(\phi), v(r) \cdot \sin(\phi), 0\},$$

$$v(r) = v_0 \left(1 - \frac{r^2}{R^2}\right).$$

Here $v_0$ is the peak velocity, $R$ the radius of the vessel, and $\phi$ is rotation in the $xy$ plane (around $z$-axis). Validation of the profiles was performed using the bias ($\hat{B}$) and standard deviation ($\sigma$), against the true profile. ($\hat{B}$) and ($\sigma$) was calculated as in [19]. In total, 16 pairs of velocity estimates were average
Parabolic flow profiles, measured on a constant flow rig (setup 1) with $v_{peak} = 0.25$ m/s. In total 10 estimates were averaged to reveal a single profile. The estimated profile is shown in red, the shaded gray area show plus minus one standard deviation, and the dashed blue line is the true profile. The top panel has a rotation of $0^\circ$ around the $z$-axis. Bottom panel a rotation of $45^\circ$.

to reveal a single profile, and in total 10 profiles were used in the validation. The peak velocity was 25 cm/s. The RC probe was fixated allowing precise calibration of $\phi$. Two settings of $\phi$ were used, $0^\circ$ and $45^\circ$, to introduce velocities in both $x$ and $y$-direction.

Setup 2 consisted of a phantom made with tissue-mimicking material with a straight vessel in the center [20], [21]. The probe was positioned above the vessel with a transducer holder, keeping the probe steady during acquisition. A closed-loop flow system (CompuFlow 1000, Shelley Medical Imaging Technologies, Toronto, ON, Canada) was used to pump blood mimicking fluid inside the vessel. The pump delivered pulsating flow with a period of 0.84 s and a peak volume flow of 10.0 mL/s, mimicking a carotid flow profile. 10 pairs of velocity estimates were averaged to reveal a single profile to avoid too high a smoothing in the temporal domain. In total 800 frames were acquired, the visualized flow and B-mode is a single frame from the series.

The penetration was estimated over 20 frames using a speckle phantom (Dansk Fantom Service, model 571) with an attenuation of 0.5dB/[cm · MHz]. The penetration depth was estimated as where the signal-to-noise ratio (SNR) crossed 0.

### III. Results

In Fig. 2 the results from setup 1 is shown. The center profile was extracted and compared to the true profile from (3). The profiles of all three components ($v_x$, $v_y$, $v_z$) are visualized. $f_{prf}$ was set at 2 kHz to limit reverberations in the water chamber. Parabolic profiles are seen for $v_z$ for both settings of $\phi$, and $v_y$ for $\phi = 45^\circ$ as expected. They are visually comparable to the true profile. The largest bias was $-17.7\%$, in the case of the highest peak velocity. The flow profiles had relative standard deviations (\(\sigma\)) of 3 to 4\% for $v_x$ and $v_y$ in both cases of $\phi$.

The volumetric velocity estimates of setup 2 are shown in Fig. 3, where flow in 3-D is visualized with arrows showing the direction and color the magnitude. The B-mode planes are shown in Fig 4. The two planes pass through the center of the vessel and are orthogonal to each other. These can be selected from anywhere in the volume. Setting $f_{prf}$ to 10 kHz can provide a B-mode volume rate above 125 Hz. Penetration was measured to 14 cm for both the flow sequence and B-mode.
The center profiles showed a high precision, i.e., low $\sigma$, but a higher bias was seen. Rotating the transducer reduces the bias for $v_x$, without increasing the bias for $v_y$. The flow is then present in both components ($v_x, v_y$) instead of only in $x$. The effect is seen when comparing the top panel to the bottom panel in Fig 2.

Using this RC array the number of channels is reduced by a factor of 16 compared to the 32x32 fully populated array. The demands for the system are therefore reduced by a factor of 16 in terms of data handling, storage, and processing. The larger surface size provides a penetration depth of 14 cm. This provides flexibility in application, as the large penetration depth could be traded for a higher center frequency.

Likewise, the interleaved sequence allows more flexibility for $f_{prf}$ to be adapted. The results demonstrate that fully volumetric vector flow imaging is achievable in 3-D with high volume rate. The use of only 62 channels, and this interleaved sequence allows it to be implemented on current scanner hardware.

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