A Direct Measurement of Inter-Element Cross-Talk in Ultrasound Arrays

DOI: 10.1109/ULTSYM.2019.8926249

A Direct Measurement of Inter-Element Cross-Talk in Ultrasound Arrays

Alessandro Ramalli
Dept. of Cardiovascular Sciences
KU Leuven
Leuven, Belgium
Dept. of Information Engineering
University of Florence
Florence, Italy
ORCID: 0000-0003-4358-3739

Jan D'hooge
Dept. of Cardiovascular Sciences
KU Leuven
Leuven, Belgium
Dept. of Circulation and
Medical Imaging
NTNU
Trondheim, Norway

Lasse Lovstakken
Dept. of Circulation and
Medical Imaging
NTNU
Trondheim, Norway

Piero Tortoli
Dept. of Information Engineering
University of Florence
Florence, Italy
ORCID: 0000-0002-7984-3128

***Abstract*— In a transducer array, spurious vibration modes generate waves propagating in the backing material, in the kerf-filler, and in the lens leading to coupled resonance of neighboring elements. It has been shown that this inter-element cross-talk may be responsible for significant distortion of the field radiated by an array, especially when large steering angles are applied. In a previous study we indirectly estimated the cross-talk by fitting one-way field measurements to simulations including an elementary cross-talk model. In this work, we present a method to directly measure and characterize the inter-element cross-talk in an array of transducers. Three array types (phased, linear and convex) were coupled to water and tested in connection to a Vantage 256 system (Verasonics). The cross-talk was estimated for different transmission amplitudes, in the range 3-45 V. Results highlight that the cross-talk on neighboring elements decays exponentially with distance from the transmitting element, while, as expected, the propagation delay linearly increases. The average cross-talk decay rate was 3.5, 3.6, 8.9 dB/pitch, while the propagation speed of the spurious wave was 921, 937, 815 m/s for phased, linear, and convex arrays, respectively.**

Keywords—cross-talk, arrays, model

I. Introduction

In the classic diffraction theory, an element of an array of transducers is typically modeled as a planar, rectangular aperture with uniform pressure over its surface [1]–[4]. However, for an element with thin width (one wavelength or less) and wide length (many wavelengths), spurious vibration modes are generated [2]. Further, in an array of transducers, the waves generated at the edges of an element, due to spurious modes, propagate in the backing material, in the kerf-filler, and in the lens, leading to coupled resonance of neighboring elements [5]–[8]. This phenomenon has been shown to be responsible for unexpected angular responses, showing drops of the pressure in transmission and reduced sensitivity in reception, which were not predicted by the classic diffraction theory [3]–[5], [7], [9].

In [10], we showed that this coupled resonance, also called inter-element cross-talk, may be responsible for significant distortion of the field radiated by the entire array, especially when large steering angles are applied. Also, in [10], we indirectly estimated the inter-element cross-talk by fitting one-way field measurements to simulations by including an elementary cross-talk model. The latter assumed that a given fraction of the signal transmitted by one element directly adds to the signals transmitted by the two adjacent elements. However, neither a cross-talk factor to second neighboring elements nor a propagation delay were included in the model.

In this paper, we present a method to directly measure and characterize the inter-element cross-talk in an array of transducers. The cross-talk factor and the propagation delay, up to the 4-th neighboring element, were experimentally estimated for three array types.

II. Methods

A. Experimental test

The experiments were based on a Vantage 256 research scanner (Verasonics, Kirkland, WA, USA), providing 256 independent channels both in transmission and reception. The system was connected to three probes with the following array types:

1. Phased array (model P4-2v, Verasonics);
2. Linear array (model L11-4v, Verasonics);
3. Convex array (model C5-2v, Verasonics).

For each array its central frequency (f_0), bandwidth (B), number of elements (nE), and pitch (p) are summarized in TABLE I, [11].

A test was conducted to assess the inter-element cross-talk of each array when immersed in water. In transmission, a 15μs-long linear chirp, spanning the bandwidth (B) of the transducers, was transmitted by one element only; in reception, all the elements of the array were enabled to receive signals for 22 μs, even during the transmission phase, and the related signals were

TABLE I. Characteristics of the Arrays

	f_0 [MHz]	B [MHz]	nE	p [μm]
Phased	3.0	2	64	300
Linear	6.3	6	128	300
Convex	3.7	2.6	128	508

This work was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 786027 (ACOUSTIC project).

recorded. The test was iterated N_e times to have each element in the array transmitting. Then, it was repeated for nA=15 transmission amplitudes, ranging from 3 to 45 V with 3 V steps.

It is worth mentioning that the Vantage system synthesizes the transmission waveforms at 250 MHz (i.e. on a 4 ns grid), and then pass them to tri-level pulsers. Hence, linear chirps were obtained by duty-cycle modulation, as proposed in [12]. Moreover, all reception-chain gains were set to their minimum to prevent, whenever possible, saturation of the analog-to-digital-converters (ADC).

B. *Estimation of the inter-element cross-talk*

For each array under test several signals were recorded, then they were reorganized in a matrix of signals $s_{e,n,a}(t)$ where t is the time, $e \in [1, nE]$ is the index of the active element in transmission, and $a \in [1, nA]$ is the index of the tested transmission amplitude. Then, $n \in [-nN, nN]$ is the index of the neighboring elements, where $n = 0$ means the receiving element that was, at the same time, transmitting the linear chirp. Finally, selecting $s_{e,0,a}(t)$ as the reference signal, the following matrix was defined:

$$R_{e,n,a}(\tau) = \text{env}\left[(s_{e,n,a} \star s_{e,0,a})(\tau)\right] \tag{1}$$

where the operator ($\star$) corresponds to the cross-correlation and the function 'env' returns the envelope of its argument. Hence, the cross-talk magnitude ($M_{e,n,a}$) and propagation delay ($T_{e,n,a}$) were defined as:

$$M_{e,n,a} = \frac{\max[R_{e,n,a}(\tau)]}{\max[R_{e,0,a}(\tau)]}; \tag{2}$$

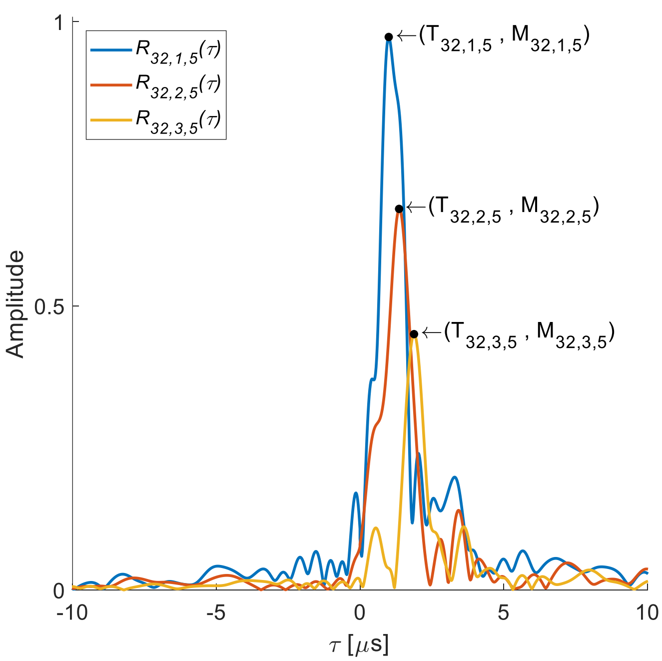

Fig. 1 Cross-correlation signals and the related cross-talk magnitude ($M_{e,n,a}$) and propagation delay $T_{e,n,a}$. In this example, the phased array was used, the linear chirp was transmitted by the central element (e=32) with an amplitude of 15 V (a=3). Only the cross-correlation signals obtained for the first (blue), the second (red) and the third (yellow) neighboring elements are shown.

TABLE II. ESTIMATED CROSS-TALK PARAMETERS

	Number of neighbors (nN)	Decay rate [dB/pitch]	Propagation velocity [m/s]
Phased	4	-3.5	921
Linear	2	-3.6	937
Convex	2	-8.9	815

$$T_{e,n,a} = \tau|_{R_{e,n,a}(\tau)=\max[R_{e,n,a}(\tau)]}. \tag{3}$$

III. RESULTS

Fig. 1 shows three examples of the envelope of the cross-correlation function. Qualitatively, it highlights how the cross-correlation function was exploited to determine inter-element cross-talk magnitude and propagation delay. Indeed, it shows that, moving from the first (blue), to the second (red), and then to the third (yellow) neighboring element, the maximum amplitude of the cross-correlation diminishes, while the propagation delay increases.

Fig. 2 clearly shows how the cross-talk magnitude on neighboring elements drops with the distance from the transmitting element. It shows that, averaging over all measurements ($nA \times nE$), the decay rate is exponential up to the fourth neighbor. In this example, i.e. for the phased array, the average decay rate was −3.5dB/pitch, while it was −3.6dB/pitch and −8.9dB/pitch for the linear and the convex arrays, respectively, as summarized in TABLE II.

Fig. 3 shows that, as expected, the propagation delay increases with the increasing index of the neighboring element. Also, it grows linearly, thus suggesting a constant propagation velocity that, as shown in TABLE II, was estimated to be 921, 937, 815 m/s for the phased, the linear, and the convex array, respectively.

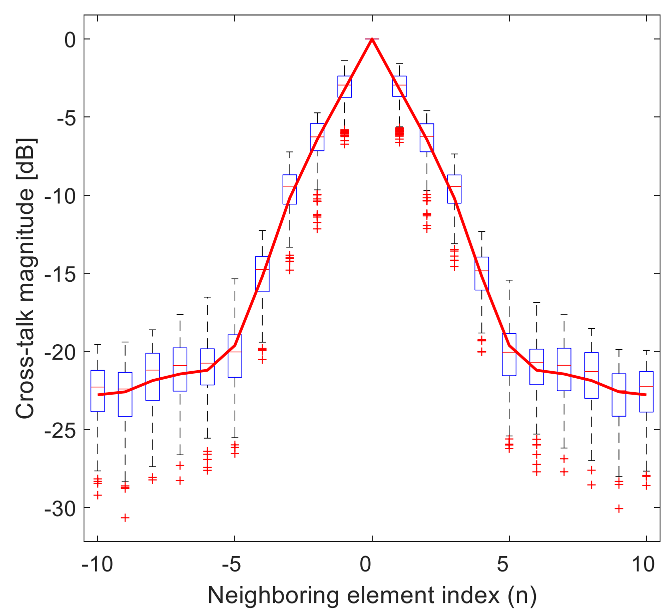

Fig. 2 Estimated cross-talk magnitude for the phased array probe. The boxplots correspond to the different measurements, i.e. 64 elements × 16 different transmission amplitudes, that are fitted by the red line.

IV. Discussion & Conclusion

A simple experimental method for the direct measurement of the inter-element cross-talk in an array of transducers was proposed and experimentally tested for three array types (phased, linear and convex) in connection to a research ultrasound scanner. The method was based on the use of a linear chirp as excitation signal to exploit its (short) auto-correlation function to estimate cross-talk magnitude and propagation delays among different neighboring elements.

The proposed method showed to be effective, as shown in the boxplots in Fig. 2 and Fig. 3. They highlight the good repeatability of the measurements, even for different transmitting amplitudes and elements, given the narrow range distribution of the estimates. Especially, the use of the cross-correlation function was effective for the estimation of the propagation delay, where the distribution range, except for some outliers, was always narrower than 0.2 µs.

Similar results were obtained for the different types of array. Among the tested samples, the convex array was the one with the lower sensitivity to cross-talk, as it showed the highest decay rate (−8.9dB/pitch). The estimates of the propagation speed confirm that we measured a wave propagating mechanically/acoustically, and not electrically, since the velocities were in the range [815, 937] m/s. Such velocities were in the same range of the propagation speed of acoustic waves in the silicone based materials, which are typically used to build the acoustic lenses.

On the other hand, the method was not sensitive enough to estimate the cross-talk on a wide range of neighboring elements; indeed, the amplitude of the received signals quickly dropped down giving noisy cross-correlation signals, thus giving noisy estimates. For this reason, as shown in TABLE II, the number of neighboring elements (nN) was limited to 4 for the phased array and to 2 for the convex and the linear ones.

Finally, it is worth highlighting that, with the proposed method, it is not possible to directly estimate the absolute cross-talk magnitude on the first neighbor. Indeed, the recorded reference signal $s_{e,0,a}(t)$ is actually the electric signal applied in transmission, while the signals recorded by neighboring elements are acoustically coupled to the transmitting one. Hence, to have an estimate of the cross-talk magnitude, the transfer function and sensitivity of the transmitting element and of the neighboring elements should be known in transmission and in reception, respectively. Nevertheless, according to what shown in Fig. 2, the decay rate between the transmitting element and the first neighbor should be similar to that of successive neighbors.

In conclusion, the direct measurement of inter-element cross-talk can be easily performed thorough the proposed method, and can contribute to develop realistic simulation models, to predict the widening of the effective element width, and thus to correct the beam distortion effect.

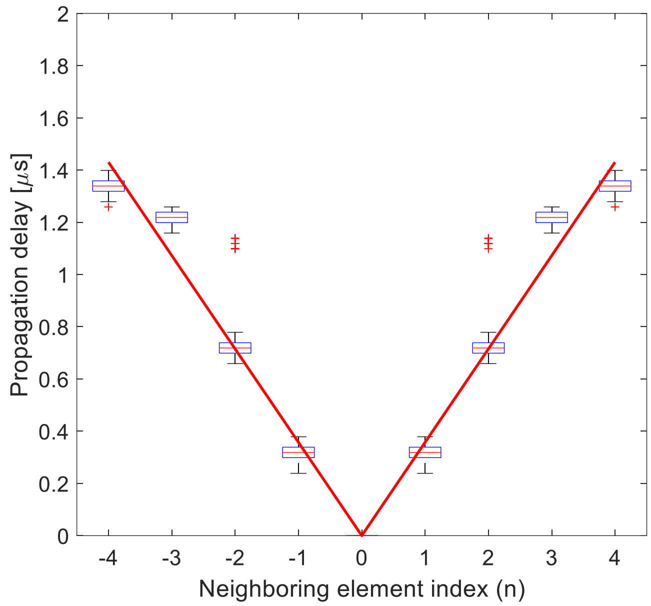

Fig. 3 Measured propagation delay for the phased array probe. The boxplots correspond to the different measurements, i.e. 64 elements × 16 different transmission amplitudes, that are fitted by the red line.

References

[1] T. L. Szabo, *Diagnostic Ultrasound Imaging: Inside Out*, 1st ed. Academic Press, 2004.

[2] A. R. Selfridge, G. S. Kino, and B. T. Khuri-Yakub, ‘A theory for the radiation pattern of a narrow-strip acoustic transducer’, *Applied Physics Letters*, vol. 37, no. 1, pp. 35–36, Jul. 1980.

[3] S. W. Smith, O. T. von Ramm, M. E. Haran, and F. L. Thurstone, ‘Angular response of piezoelectric elements in phased array ultrasound scanners’, *IEEE Transactions on Sonics and Ultrasonics*, vol. 26, no. 3, pp. 185–190, May 1979.

[4] W. Friedrich, H. Kaarmann, and R. Lerch, ‘Finite element modeling of acoustic radiation from piezoelectric phased array antennas’, in *Ultrasonics Symposium, 1990. Proceedings., IEEE 1990*, 1990, pp. 763–767 vol.2.

[5] B. Delannoy, C. Bruneel, F. Haine, and R. Torguet, ‘Anomalous behavior in the radiation pattern of piezoelectric transducers induced by parasitic Lamb wave generation’, *Journal of Applied Physics*, vol. 51, no. 7, pp. 3942–3948, Jul. 1980.

[6] J. D. Larson, ‘Non-Ideal Radiators in Phased Array Transducers’, in *1981 Ultrasonics Symposium*, 1981, pp. 673–684.

[7] G. S. Kino and R. Baer, ‘Theory for Cross-Coupling’, in *1983 Ultrasonics Symposium*, 1983, pp. 1013–1019.

[8] J. F. Guess, C. G. Oakley, S. J. Douglas, and R. D. Morgan, ‘Cross-talk paths in array transducers’, in , *1995 IEEE Ultrasonics Symposium, 1995. Proceedings*, 1995, vol. 2, pp. 1279–1282 vol.2.

[9] N. Felix, D. Certon, E. Lacaze, M. Lethiecq, and F. Patat, ‘Experimental investigation of cross-coupling and its influence on the elementary radiation pattern in 1D ultrasound arrays’, in *1999 IEEE Ultrasonics Symposium, 1999. Proceedings*, 1999, vol. 2, pp. 1053–1056 vol.2.

[10] A. Ramalli, P. Tortoli, A. S. Savoia, and G. Caliano, ‘Improved array beam steering by compensation of inter-element cross-talk’, in *Ultrasonics Symposium (IUS), 2015 IEEE International*, 2015.

[11] Verasonics Inc., ‘Verasonics Transducers’, *Verasonics*. [Online]. Available: https://verasonics.com/verasonics-transducers/. [Accessed: 26-Aug-2019].

[12] A. Ramalli *et al.*, ‘Multi transmit beams for fast cardiac imaging towards clinical routine’, in *2016 IEEE International Ultrasonics Symposium (IUS)*, 2016, pp. 1–4.