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Influence of SAFT Activation Sequence in 2D Arrays Performance

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***Abstract*—In this work we present a comparison between several beam patterns obtained with a conventional SAFT technique, where only one element in emission and other in reception are used, applying different activation sequences of the elements of a two-dimensional array. As we show, different activation sequences produce different beam patterns, demonstrating thus that not only the elements used to emit and receive the signals determine the radiation pattern, but also the sequences in which these elements are activated. Thus, the coarray becomes an essential tool to analyze the radiation pattern generated when synthetic apertures techniques are applied over two-dimensional arrays.**

Keywords: 2D array;coarray

I. Introduction

The synthetic aperture focusing technique (SAFT), where only one element of the array is activated sequentially to emit and receive, has been a topic profusely studied in several application areas, such as radar [1, 2], sonar [3] or ultrasonic imaging [4, 5]. This technique allows reducing drastically the volume and complexity of the imaging systems, limiting the number of hardware channels and decreasing the total cost of the system.

In the last years, a considerable effort has been focused on developing 3D real-time scanners based on 2D phased-arrays [6, 7]. In this context, the interest on the synthetic aperture techniques has increased, mainly considering that, under certain conditions, they can, not only reduce the hardware, but also accelerate the image composition [8].

The synthetic aperture technique (SAFT) applied on linear arrays typically use the same element to emit and receive, producing a beam pattern with grating lobes. This is because the elements of the coarray (also referred as "effective aperture" in the ultrasound literature [9]) are spaced by one wavelength [10]. Nevertheless, working with two-dimensional arrays, the degrees of freedom are increased, and it is possible to consider other forms of sequential activation of the array elements.

In this work different emit-receive strategies, which we call "activation sequences", are studied and evaluated through the 2-D distribution and gain of the elements in the coarray.

The coarray resulting from applying SAFT over a 2-D array can be easily calculated as the sum of the subcoarrays obtained convoluting each pair of subaperture in emission and reception [11]. Just like the coarray has been used as a way to quickly analyze the radiation properties of linear arrays [12-16], it can also be very useful in the two-dimensional case, facilitating the analysis of the beam pattern generated when SAFT is applied over the 2-D array. As it is well known, the coarray is the aperture that would produce in one-way the same two-way radiation pattern of the original imaging system [17].

In the experimental part of this work, a squared array with 11x11 elements regularly distributed in a matrix grid is used. In this case, the coarray is a squared matrix with 21x21 elements. With different activation sequences we obtain different coarrays and consequently, different radiation patterns, although always one element in emission and one in reception is used.

II. The Bidimensional Coarray

If the elements of the 2-D array are distributed in a squared matrix, such as happens in our case, the subapertures, subcoarrays and coarray can be mathematically expressed as a matrix of data, where the numbers correspond with the gain applied to each one of the array elements. Thus, the subapertures in emission and in reception will be represented by matrix with NxN elements, where each one contain the gain applied to each element in every firing sequence. The subcoarrays will be represented by matrix with (2N-1)x(2N-1) elements, obtained by the two-dimensional convolution of each pair of emission-reception subaperture matrixes. The coarray will be the sum of all subcoarrays.

Fig. 1 shows the process to calculate the coarray and the beam pattern obtained when SAFT is applied over a 2-D square matrix array with 2x2 elements spaced $\lambda/2$. Thus, the cubes represent the gain of the active elements in each moment. In this case there are as many subapertures as elements in the array, because only one is active each time.

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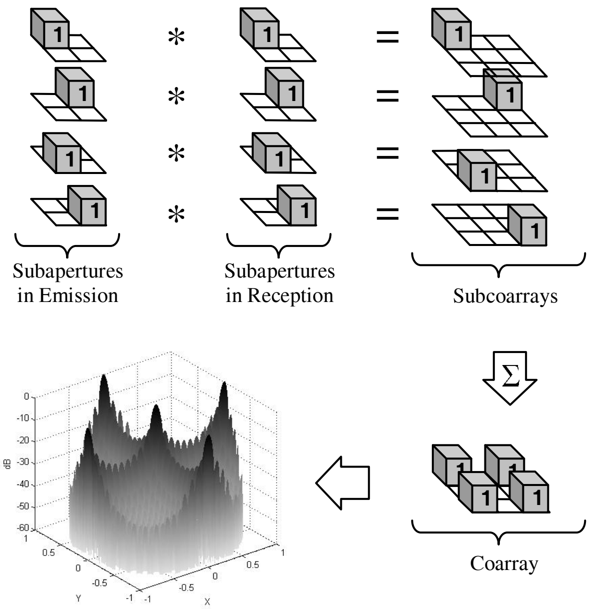

Figure 1. Subapertures in emission and reception, subcoarrays, coarray and beam pattern generated applying a SAFT over a 2-D array with 2x2 elements spaced λ/2.

As we can see, in this case the subcoarrays have 3x3 elements, resulting from making the convolution of two matrixes with 2x2 elements. Adding the subcoarrays all together we get the coarray implemented with this sequence of activation, which has an equivalent distance of λ between their elements, and consequently, the beam pattern generated presents grating lobes in the main directions. (In order to make this situation more perceptible, the beam pattern showed corresponds actually with a larger array with 11x11 elements)

From now, we will express the coarray as a matrix of data, because this is a simple and fast form of representation of the apodization.

III. Analisys of the Activation Sequences

Thinking on the example shown in the former section, where SAFT is applied using the same element to emit and receive the signals, it is possible to infer that other ways to combine the active elements in emission and reception are possible. Thus, we refer as "activation sequence" to all this different ways to combine the active elements in emission and reception.

Unlike what happens in the case of linear arrays, with two-dimensional arrays there are a lot of different ways of activating the elements. Furthermore, as we will see later, the activation sequences modify the beam pattern generated.

The study of all the activation sequences available to apply on a two-dimensional array can be an oversized problem, due to the amount of possible cases. For that reason, the use of the coarray turns out to be an essential and indispensable tool for studying the application of a synthetic aperture over a 2-D array, as it facilitates the analysis of different possible combinations and provides a fast and clear idea of the radiation patterns corresponding to the different sequences that it is possible to apply.

As an example of the effect of the activation sequences on the radiation pattern generated by a 2-D array, we consider a 2-D squared matrix array with 3x3 elements spaced λ/2, to which several activation sequences are applied, in such a way that only one element with unity gain is used each time to emit and receive the signals. As we have seen in the previous section, the resultant coarray can be expressed as a matrix with 5x5 elements, where the value of each element represents the apodization of each virtual element of the coarray.

Altogether, eight different activation sequences are studied. To simplify the analysis, we have supposed that the elements in emission always are excited in the same way, whereas the activation sequence of the receivers is modified respect to the conventional case. Fig. 2 shows these eight activation sequences (S_{11}, S_{12}, S_{13}, S_{14}, S_{21}, S_{22}, S_{23}, S_{24}). Thus, each combination consist on emitting (Tx) and receiving (Rx) with only one element, which is sequentially activated as shown with arrows over the diagrams. According to the scheme shown in Fig. 1, by each activation sequence there are nine subapertures in emission and nine in reception, which convolved together, generate nine subcoarrays. Adding the subcoarrays all together we get the final coarray produced by the corresponding activation sequence. Fig. 2 presents the eight different coarrays obtained with every activation sequence.

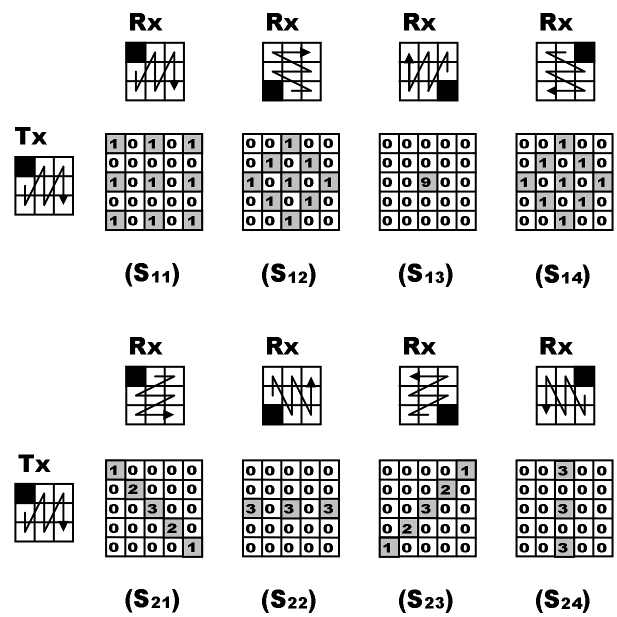

Figure 2. Coarrays obtained applying eight different activation sequences (S_{ij}) to the elements of a 2D squared matrix array with 3x3 elements spaced λ/2.

One property of these coarrays is that the sum of their weights is always constant and equal to nine. This is a logical result, because we always emit and receive the same number of times and all the elements of the original array present the same gain.

Fig. 3 shows the simulated radiation patterns, in far-field and with narrow-band excitation signals, obtained with the previous array and the different activation sequences applied (S_{ij}). The images represent the maximum value of the acoustic field in a hemisphere located over the array. The radiation patterns are observed with an elevation of 90 degrees respect to the plane of the array. The images are displayed over -40dB dynamic range.

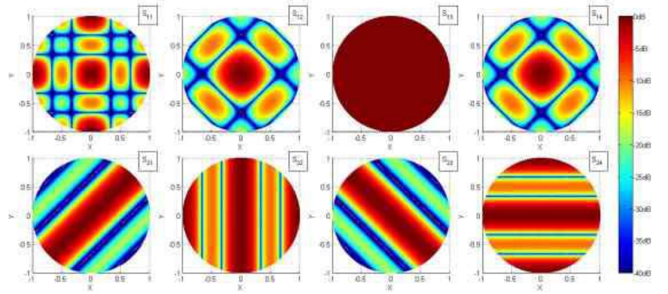

Figure 3. Radiation patterns obtained applying 8 different activation sequences (S_{ij}) to the elements of a 2D squared matrix array with 3x3 elements spaced $\lambda/2$.

Thus, depending on the activation sequences applied, different beam patterns are obtained. Whereas the first sequence (S_{11}) produces the typical beam pattern with grating lobes of the conventional SAFT, others, such as S_{12} and S_{14}, suppress the grating lobes because they present equivalents arrays spaced $\lambda/2$ in the principal axes and spaced $\lambda/\sqrt{2}$ in the diagonals, being the grating lobes outside of the visible region, obtaining thus a radiation pattern more similar to the full array case. Nevertheless, there are other sequences, like S_{13}, that produce an isotropic radiation pattern, equivalent to emit and receive with only one element located in the centre of the array, with a gain nine times higher.

The last four sequences (S_{21}, S_{22}, S_{23}, S_{24}) produce beam patterns similar to the linear arrays, as their coarrays have the elements in only one direction. Whereas the sequence S_{22} and S_{24} have grating lobes, because the elements in their coarray are spaced λ, the sequences S_{21} and S_{23} show a separation of $\lambda/\sqrt{2}$ between the elements of their coarrays, and the grating lobes are located outside of the visible region.

IV. RESULTS

In order to evaluate the theoretical results presented in the previous sections, we have made a set of measurements with a real imaging system. A 2D square matrix array transducer with 11x11 elements (IMASONIC, mod. 7038-A101) has been used in the experiments. The transducer works at 3MHz and has a kerf of 0.2mm and a pitch of 1mm in both directions, corresponding approximately with a gap of $\lambda/2$ in steal. The transducers present a 50% of relative bandwidth. A SITAU 128:128 equipment, manufactured by DASEL S.L, has been used to obtain the images.

A piece of steal (21cm x 21cm x 10cm) has been used to make the measurements. It has been drilled a 2mm diameter hole with a depth of 3cm in the centre of the bottom face, being at 7cm from the top face, where the transducer is located. The piece is big enough to consider that no echo coming from the walls are registered in the scanned images. The speed of sound on the piece is approximately 6’22 mm/µseg. Fig. 4 shows a diagram of the system used for the measurements. The grey area represents the volume of the piece that has been scanned with the imaging system. This volume is contained between a hemisphere of 6cm radius and other of 9cm radius.

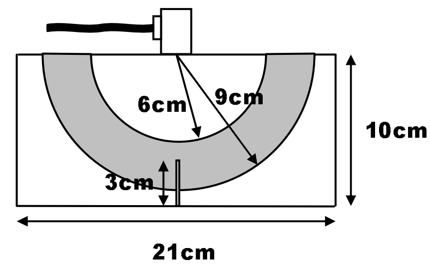

Figure 4. Scheme of the system used to make the acquisitions.

Using this experimental setup, the eight activation sequences (S_{ij}) showed in the previous section have been implemented. These sequences, applied on the transducer of 11x11 elements, produce coarrays that can be expressed by matrixes with 21x21 elements but, due to their big size, they are not presented here. Nevertheless, their shape is equivalent to the one shown in Fig. 3, being only different the weights of the elements (e.g. the sequence S_{13} produce now a coarray with a gain of 121). The next figure shows the beam patterns generated on this peace when these activation sequences are applied on our transducer.

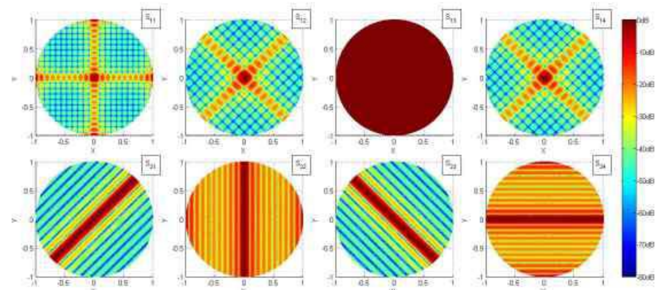

Figure 5. Radiation patterns obtained applying 8 different activation sequences (S_{ij}) to the elements of a commercial 2D squared matrix phased array with 11x11 elements.

Eight experimental acquisitions have been done using the different sequences. They were made emitting and receiving according to the schemes proposed, storing the captured signals and post-processing all together to form every line of the volume. All signals are then dynamically focused on emission and reception in order to obtain the images. The volume has been scanned in 91 positions in elevation and 360 positions in azimuth. Fig. 6 shows a noisy signal acquired with one of the elements (a) and another one corresponding to the central line of S12 sequence (b).

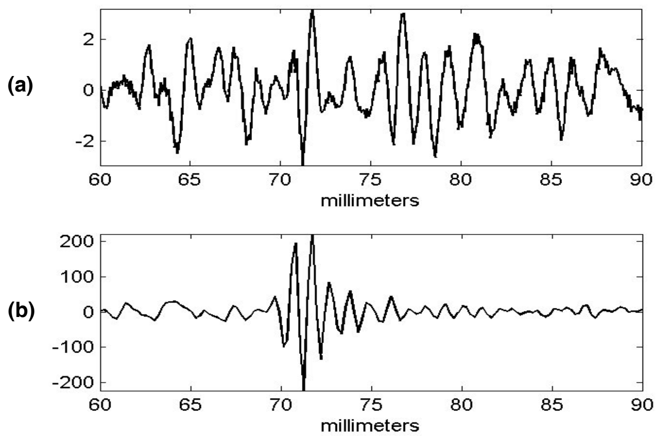

Figure 6. Example of a signal adquired with one element (a) and the resultant central line of S_{12} sequence, obtained combining the 121 signals received (b).

The signals have been sampled at 40MHz. Due to the small size of the elements, the echo from the hole can hardly be distinguished from the noise contained. Fig. 7 shows the maximum value of each line, displayed over -25dB dynamic range.

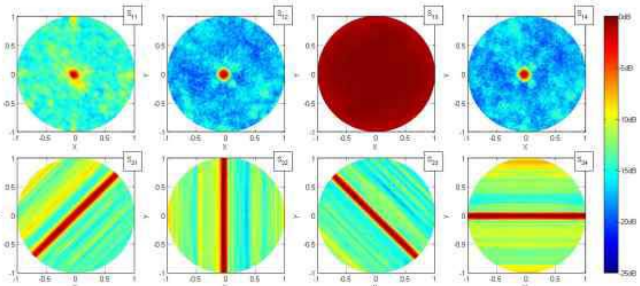

Figure 7. Maximum value of each line of the volumes scanned with the commercial 2D squared matrix phased array. Each volume has been obtained using applying a different activation sequence (S_{ij}) on the transducer.

As we can see, the measurements match perfectly with the theoretical deductions made on the previous section. Only a difference in contrast can be observed due to the noise contained in the signals. Thus, with the S_{11} sequence, grating lobes appear in the image, whereas with the S_{12} and S_{14} sequence a radiation pattern more similar to the full array case is achieved. The typical SAFT, corresponding to the S_{11} sequence, produces images with lower contrast than the S_{12} sequence, although it is also possible to verify how the sequences S_{12} and S_{14} present a worse lateral resolution than the S_{11}, such as it was predicted theoretically. The rest of the images also correspond with the theoretical assumptions, although they can present small differences due to the vertical misalignments between the hole and the transducer. In spite of this, the obtained results match clearly with the ones expected.

V. Conclusions

This work has given examples of how different activation sequences applied over two-dimensional arrays can modify the beam pattern. Thus, a SAFT configuration where a different element is used to emit and receive the signals has been studied over a 2D squared matrix phased array. The results reveal the convenience of using the coarray to analyze the different ways of activating the elements of the array. Experimental results have confirmed the theoretical deductions, showing how some activation sequences suppress the grating lobes, producing better image contrast than the conventional SAFT solution, where the same element is used for emission and reception.

VI. References

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