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Method to determine far-field beampattern of long array from subarray beampattern measurements

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ABSTRACT

Beampattern measurement is essential to verify the performance of an array sonar. However, common problems in beampattern measurement of arrays are the constraints to achieve the far-field condition and reach plane waves due to aspects such as limited measurement space. We aimed to measure an array beampattern in limited space and evaluate the performance through the –3 dB beam width. Hence, we devised a method to measure the beampattern of a discrete line array in limited space based on the subarray method. Specifically, a discrete line array whose measurement space does not satisfy the far-field condition is divided into several subarrays that satisfy this condition, and the beampattern of the line array is then determined from subarray measurements. The proposed method is verified by simulations, and we performed a measurement experiment on a line array with 256 elements and a design frequency of 455 kHz. The proposed method accurately determines the beampattern of the line array through a simple approach compared to beampattern conversion obtained from measurement data from the near up to the far-field.

Keywords: Beampattern, Near-field

1. INTRODUCTION

Beampattern measurement is essential to verify the performance of array sonar. However, such measurement for long arrays generally needs a huge testing field or a complex setup (1,2). Especially for long arrays operating at high frequencies, it is difficult to measure beampatterns in acoustic tanks.

We intended to measure the beampattern in a limited space for performance evaluation through the –3 dB beam width of the array. Near-field scanning can be applied to a very large (or long) array, for which the far-field distance becomes prohibitive regarding the achievable experimental test range or dimension of the acoustic tank. This way, effective performance measurements of a large array can be achieved. However, as near-field scanning is very time-consuming (3), we propose a method based on subarrays to measure the beampattern of a long line array in a limited space. We verified the proposed method through numerical simulation and then experimentally measured the beampattern of an array.

2. METHODS

2.1 Beampattern

A beampattern represents the intensity variation of a beam as function of its direction and distance from its source. Beamforming is a technique used to send (receive) signals over (from) a specific direction. It can be achieved through spatial filtering by using a sensor array or through signal processing. The beampattern of a discrete array can be determined by summing the products of the phase differences and the delay functions of all of the array elements by considering the constructive and destructive interference of signals at a specific angle (4). When the same omnidirectional elements

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are uniformly arranged over a plane, as shown in Figure 1, and assuming no mutual coupling among elements, the beampattern is given by

$$B(\theta,\phi) = \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{l=1}^{L} g(x,y,z)\cdot exp\left[(m-1)\psi_x + (n-1)\psi_y + (l-1)\psi_z\right] \qquad (1)$$

where angles θ and ϕ are as described in Figure 1, m, n, and l correspond to values along axes M, N, and L in Figure 1, respectively, $g(x,y,z)$ is the aperture function, and (ψ_x, ψ_x, ψ_x) are expressed as

$$\psi_x = Kd_x \cos\theta\cos\phi$$
$$\psi_y = Kd_y \sin\theta\cos\phi \qquad (2)$$
$$\psi_z = Kd_z \sin\theta$$

with K being the wavenumber of the detected signal frequency and d the interval between elements (4–6). Beampattern B is defined for plane waves of sound because they satisfy the far-field conditions.

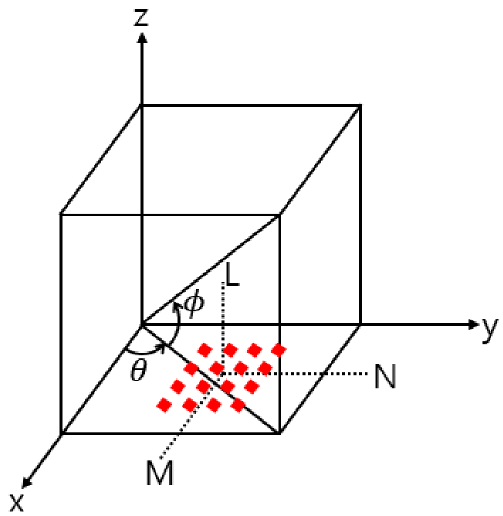

Figure 1 – Geometry of uniform rectangular array, where each element is a red diamond

2.2 Proposed Measurement Method

For a discrete line array whose measurement space does not satisfy the far-field condition, the proposed method for obtaining the beampattern from near-field measurements divides the array into several subarrays, each satisfying the far-field condition. Then, it is possible to derive the beampattern of the array by assuming each subarray to be one element contributing a beampattern. The aperture function of the line array consisting of subarrays is given by

$$g(x) = \sum_{n=1}^{N} g_n(x - x_n) \qquad (3)$$

where x_n is the position of the subarray and g_n is the aperture function of subarray n. If the aperture functions for all the subarrays are the same and for a sampling function as in Equation 4, the aperture function of the array can be written in the convolution form shown in Equation 5, where $*$ denotes convolution.

$$D(x) = \sum_{n=1}^{N} \delta(x - x_n) \qquad (4)$$

$$g(x) = g_n(x) * D(x) \qquad (5)$$

As convolution in spatial coordinates is multiplied by the angular area of the beampattern, the total beampattern can be obtained as

$$B(\theta,\phi) = B_n(\theta,\phi) \times B_D(\theta,\phi) \qquad (5)$$

which corresponds to the beampattern of the subarray multiplied by the beampattern of the sampling function.

3. SIMULATION AND EXPERIMENTS

3.1 Numerical simulation

To verify the effectiveness of the proposed method, we first performed a simulation on a line array with 256 omnidirectional antenna elements at a design frequency of 455 kHz. The array was divided into 16 subarrays, each having 16 elements. The beampattern for the far-field condition and that using the phase difference of each element at the near-field (r = 2.44 m) are shown in Figure 2. Although the ideal far-field beampattern corresponds to a sinc function, the beampattern using the phase difference for the near-field in Figure 2 substantially differs from the far-field beampattern.

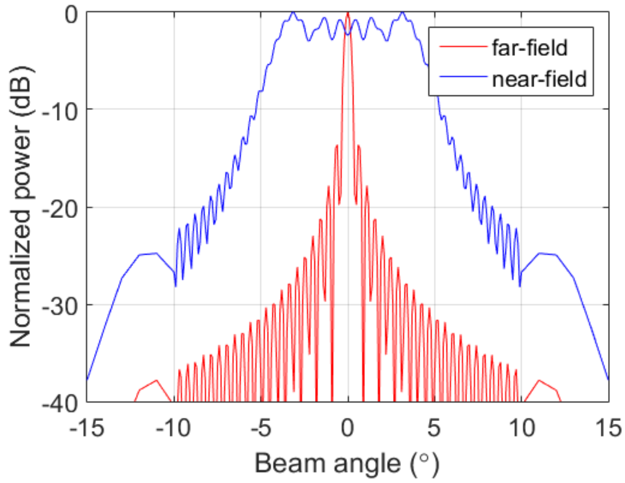

Figure 2 – Beampattern simulation for far-field and near-field (r = 2.44 m)

The beampattern of each subarray and that of the sampling function to obtain the total beampattern using the proposed method for the far-field are shown in Figure 3. The beampattern obtained from the results of Figure 3 through the proposed method are shown in Figure 4. The calculated and simulated (Figure 2) beampatterns suitably agree, confirming the correctness of the proposed method.

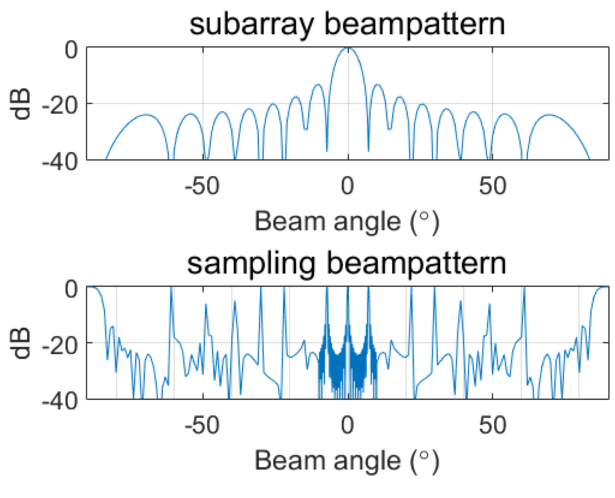

Figure 3 – Beampattern of subarray (top) and sampling function (bottom) in far-field

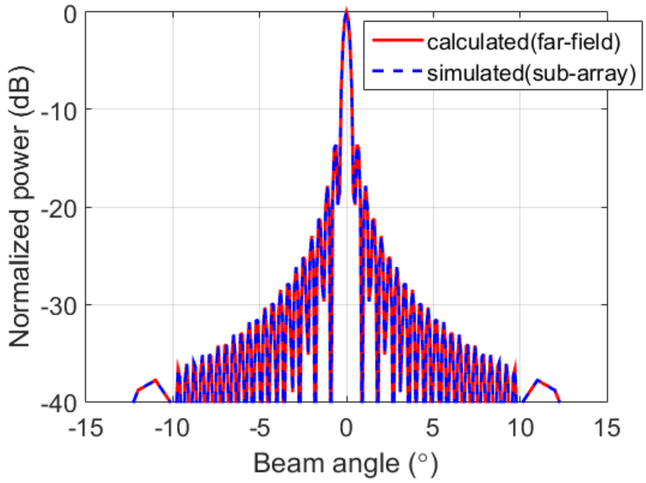

Figure 4 – Far-field beampattern verifying the proposed method

The beampattern obtained from the near-field (r = 2.44 m) phase difference using the proposed method is shown in Figure 5 and confirms that the far-field beampattern can be obtained by applying the proposed method to near-field measurements.

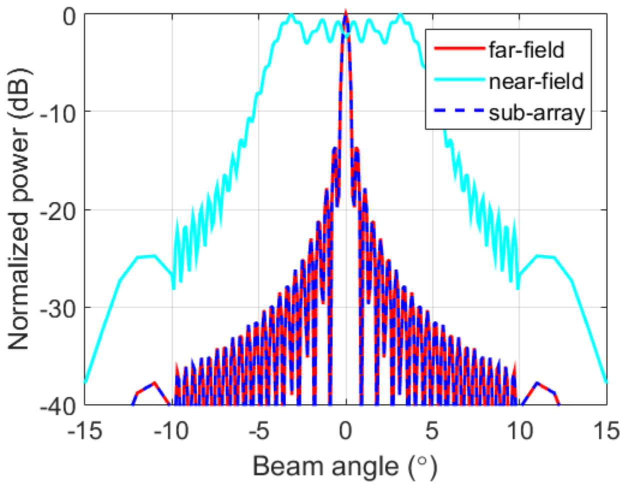

Figure 5 – Beampattern for near-field obtained by proposed method and beampattern for far and near field

3.2 Experiments

To obtain a real beampattern and further verify the proposed method, we performed near-field measurement experiments on an array as that from the simulation placed within a 4 × 4 × 5 m acoustic tank. For near-field measurements, the distance between the transmitter and receiver was 2.66 m, and the measurement angle ranged from –50 to 50° at intervals of 1°. In addition, we considered a measurement interval from –10 to 10° for the main lobe with resolution of 0.1° and a sampling frequency of 10 MHz. We obtained the beampattern from near-field measurements to determine the performance through the –3 dB beam width of the array, and hence we limited the range of measurement angles.

Figure 6 shows the examples of beampatterns obtained using data measured in the near-field for various subarrays. Although all the elements that comprise the array are nearly omnidirectional, this feature is not ideal, and there are measurement errors that cause a small differences in beampatterns among subarrays. To obtain the total beampattern of the array through the proposed method, we assumed that the beampatterns of all subarrays are equal. Therefore, in this experiment, the average beampattern from the measured subarrays shown in Figure 7(a) was used as representative beampattern, and the sampling beampattern shown in Figure 7(b) was used to apply the proposed method.

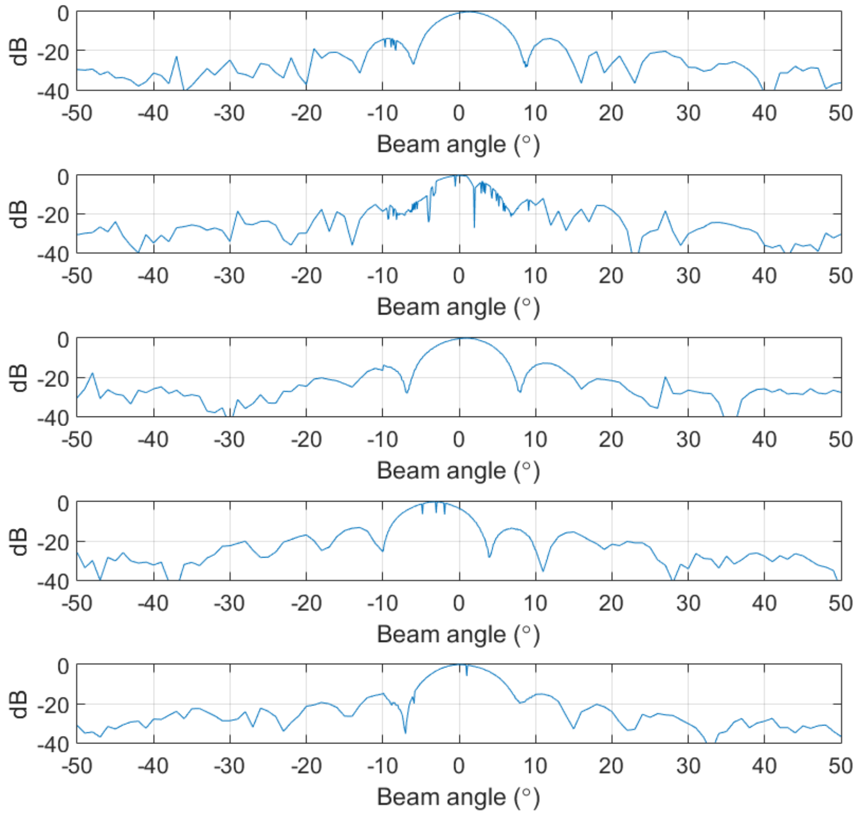

Figure 6 – Examples of subarray beampatterns obtained from near-field measurements

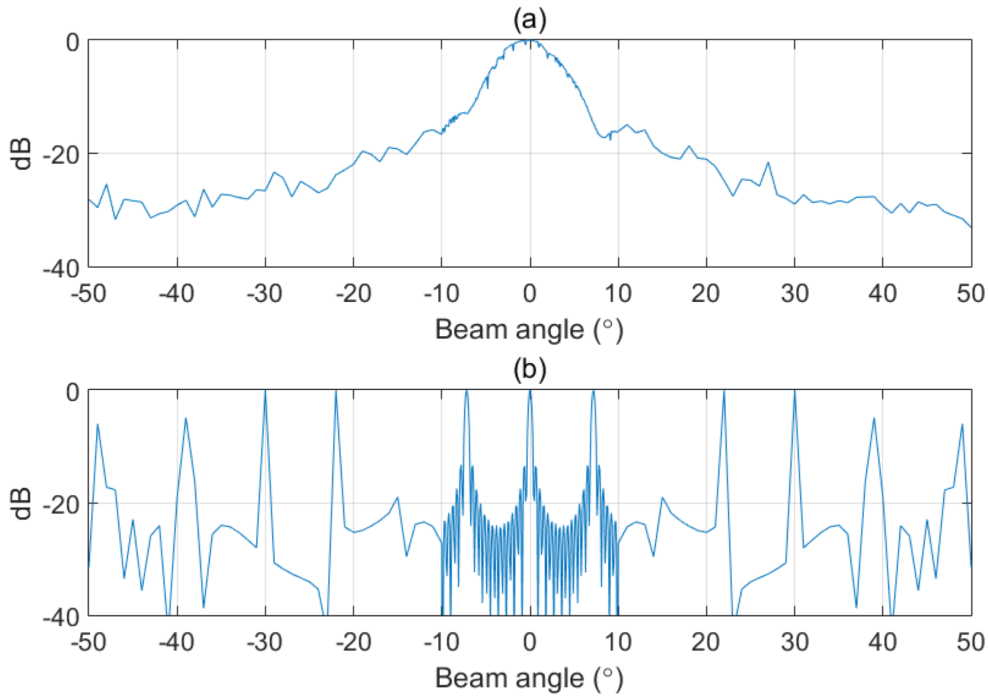

Figure 7 – Subarray beampattern to obtain total beampattern using the proposed method. (a) Subarray beampattern obtained from near-field measurements and (b) sampling beampattern

The main lobe of the array beampattern obtained from the proposed method with the results in Figure 7 is shown in Figure 8 (blue line). For comparison, the figure also shows the beampattern obtained from simulation (red dashed line) for an array of 256 omnidirectional elements. The proposed method can suitably retrieve an array beampattern from near-field measurements and be employed to evaluate the performance of the array given the –3 dB beam width.

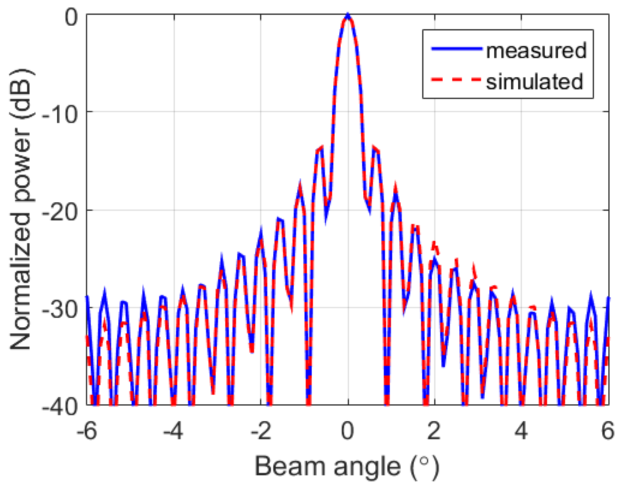

Figure 8 – Beampatterns obtained from simulation and proposed method

4. CONCLUSIONS

We aimed to measure the beampattern of an array to evaluate its performance over the –3 dB beam width. However, the usually limited available space for beampattern measurements impedes satisfying the far-field condition of the array. We overcome this problem using a method to obtain the beampattern of the arrays through near-field measurements when the far-field condition cannot be achieved due to limited space. Through a simulation, we verified the effectiveness and accuracy of the proposed method. In addition, we experimentally verified the proposed method by obtaining the beampattern of an array through near-field measurements. When measuring beampatterns of arrays, the far-field condition is usually not satisfied, and far-field measurements present various problems related to the transmission of sound waves. Therefore, the near-field beampattern measurements enabled by the proposed method can be used in a variety of practical cases.

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