PROTOTYPE SPARSE ARRAYS FOR 3D SONAR IMAGING SYSTEM

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ABSTRACT

A three dimensional sonar imaging system is under development for use by Navy divers for mine-field reconnaissance and mine-hunting systems. These divers require a small, low power, lightweight acoustic imaging system with high resolution for examining and disposing of underwater ordinance. Sparse array technology is being investigated to develop a sonar requiring the minimal number of signal processing channels while maintaining the beamwidth and sidelobe structure required for high resolution imaging. Beamwidth and sidelobe structure are examined as a function of transducer element count, channel bandwidth, and element location when optimized using various cost functions. Test results for a prototype line array evaluated in the NUWC Acoustic Test Facility are reported.

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1. INTRODUCTION

For undersea acoustic minefield reconnaissance and mine hunting by divers, a handheld, low cost sonar system is needed. To achieve these goals, Teratech Corporation, of Burlington, MA, is designing and building a high-resolution, three-dimensional sonar imaging system based on a large-area electronically steerable two-dimensional sparse array. The system under development will provide continuous real-time scanned images throughout a 20^{o} field of view. The beamforming will be implemented using multiple CCD/CMOS, time-domain delay-and-sum circuits. A delay-and-sum beamformer allows a 2D array to "look" for signals propagating in a particular direction. By adjusting the delays associated with each element of the array, the array's directivity can be electronically steered toward the source of radiation. By systematically varying the beamformer's delays and its shading along a 2D imaging plane, a 2D scan response of the array can be measured, and the resulting 2D images representing the 3D radiation sources can be created.

The delay-and-sum beamforming approach allows target range information to be obtained from the time-of-flight calculations. When a target area is identified by the proposed electronically steerable sonar system, the beamforming electronics can be adjusted to zoom-in to a smaller field-of-view for high-resolution imagery. Critical components being developed are the following: a large-area, low-insertion loss and high-bandwidth sparse array, a 32-channel beamforming processor, a bank of low-noise amplifiers, and CDP FIR filters for baseband signal conversion. The beamforming electronics and FIR filters will be developed based on high-throughput charge-domain-processing (CDP) technology, Chiang (1). The processing requirements are to provide image updates at a rate of four frames per second. The resolution of an imaging sonar in azimuth and elevation is directly proportional to its aperature in wavelengths.

The overall goal of this effort is to develop an acoustic system capable of imaging with 1 cm^3 resolution at a range of 3 meters. To meet this requirement, velocity of sound dictates a tradeoff between acoustic frequency and physical size of the array. This paper describes development of a 20 cm. x 20 cm., 2 MHz sparse array providing a 0.21 degree main beamwidth which is currently in the design stages.

2. RECEIVE ARRAY DESIGN

A fully populated 20 cm. x 20 cm. array would have transducer elements at half-wavelength ($\lambda/2$) spacing. At 2 MHz, assuming a velocity of sound of 1500 m./sec., this would be an array of approximately 512 x 512 transducer elements or 262,144 total elements. At λ spacing, the array would still require 65,536 elements. It is impractical to provide that many channels of signal conditioning and beamforming in a portable system. Benjamin (2) describes a sparse ultrasonic imaging array, using 1728 of 280,900 individual diced PZT elements. A similar array design was evaluated using a pseudo-random distribution of 23 x 23 elements. If the elements of a partially filled array are uniformly spaced, grating lobes are produced. Element locations were therefore computed by jittering element position in a uniform 20 cm. planar array within a range of $\pm$ 0.5 the inter-element distance. The output signal-to-noise ratio is proportional to the number of active elements, Steinberg (3). This array had a filling factor of 0.8% which corresponds to a loss in SNR of 21 dB. To compensate for some of the losses, a broadband fm slide is transmitted and the array output is matched filtered.

The response of the array is computed as the square of the matched filtered output as derived by Kay (4). The power at the beamformer /matched filter output for a signal arriving from an angle θ_x, θ_y is therefore

$$\mathrm{B}(\theta_x, \theta_y) = \left(\frac{1}{M^2} \sum_{i=0}^{M^2-1} w_i \cos(2\pi F_o \tau_i) \frac{\sin(\pi \tau_i W)}{\pi \tau_i W} \right)^2 \tag{1}$$

where τ_i is the time delay to the ith sensor, W is the bandwidth, F_0 is the center frequency, w_i is the weight applied to the *ith* element and M is the number of sensors in each dimension. The ith sensor is located at $\mathbf{r}_i = (x_i, y_i)$, $\mathbf{u}$ is the unit vector in the direction of propagation and c is the speed of sound.

$$\tau_i = \frac{\mathbf{u}^T \mathbf{r}_i}{c} = -\frac{1}{c}(x_i \cos\theta_x + y_i \cos\theta_y) \tag{2}$$

3.0 RECEIVER ARRAY OPTIMIZATION

A method of optimization was developed for the design of non-uniformly sparse partially-filled broadband imaging arrays. This method employed a grid point search technique to iteratively evaluate an optimization criterion. This corresponds to an optimization using a maximum over each variable and is termed the relaxation method, Pierre (5) or stepwise regression in the statistical literature, Bard (6). The grid points consist of all the possible locations a sensor may occupy in the planar array. A search of the grid points achieves a locally optimum solution. The optimization criterion is a cost function, which integrates the sidelobe energy over a range of steering angles. The primary goal of the optimization algorithm is to minimize the side lobe energy for a given number of sensors and bandwidth. Specifically, this is done by iteratively evaluating the optimization criterion for the possible array configurations. Three cost functions were explored for the optimization process. Minimizing the weighted average sidelobe energy $\overline{J}$ over the region of interest,

$$\overline{J} = \frac{1}{2u_{\max}^2} \iint_S W(u_x, u_y) B(u_x, u_y) du_x du_y \tag{5}$$

where the weighting function, $W(u_x, u_y)$, applies more weight to regions in the array response that require side lobe reduction out-performed minimizing the average sidelobe energy or peak sidelobe energy over the same region.

The optimization began with a two-dimensional pseudo-random array. An initial issue with the pseudo-random array was that the first sidelobe was at –13 dB. To minimize the first sidelobe and therefore blurring of the image pixels, the lower limit, u_0, was set to the end of the main lobe. Based on previous designs of acoustic imaging systems with acoustic lens by Ultra-Acoustics Inc, Folds (7), a design goal was set at –25 dB for the first sidelobe. Several configurations of element count and channel bandwidth were evaluated for size, power and compatibility with CDP technology throughput. Using this analysis, a configuration of 225 elements, 667 kHz bandwidth was selected. Figure 1 is a plot of the array performance, sensitivity versus cross range, for a 225-element sparsely-sampled array at 2 MHz. The peak to maximum sidelobe level is approximately 29 dB. The modeling of this performance, to achieve the maximum main lobe to clutter level ratio possible, was independently verified, Folds(7).

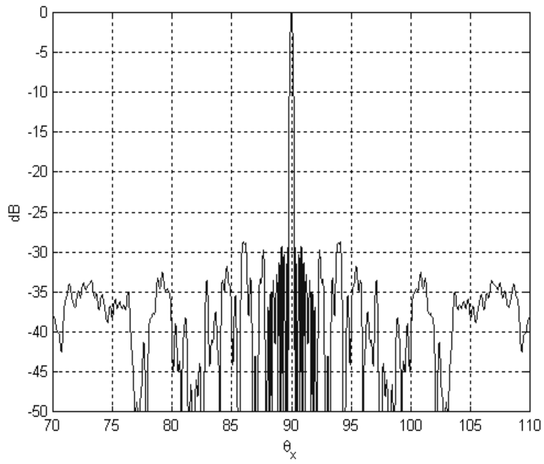

Figure 1: A slice through the x-axis (elevation) of the sparsely sampled 15 x 15 element 2D sonar array.

4. PROTOTYPE ONE DIMENSIONAL ARRAY

A 20 cm. one dimensional sparse array was designed using the approach in Kay (8). It was fabricated by Tetrad Corp, Englewood, CO and tested in the NUWC Acoustic Test Facility. The array was 264 elements across, with a pitch of .781 mm. From this array, 32 elements were active. Figure 3 shows the predicted response for a 2 MHz array, 667 kHz array. Figure 5 shows the measured near-field beampattern for a source at 3 meters for the prototype array as obtained in the NUWC Acoustic Test Facility. The free-field voltage sensitivities of the individual active elements were measured at approximately –250 dB //V/ µPa over the frequencies of interest. The first sidelobes were typically 18 dB down. The average source level over the bandwidth of the fm slide was 192 dB re µPa. Performance was principally limited by electronic noise from the built-in pre-amps.

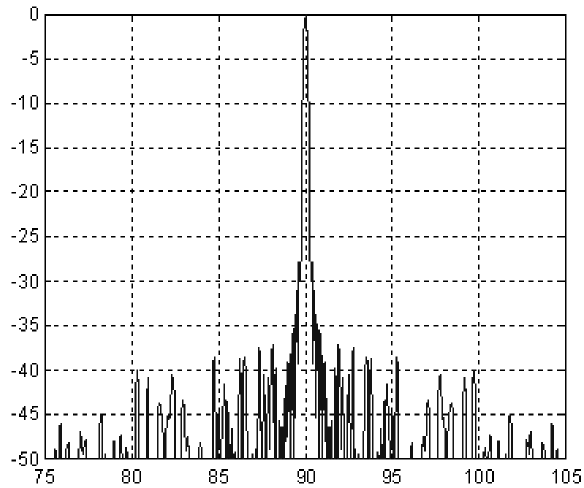

Figure 3. Predicted beampattern for 20 cm. one dimensional array.

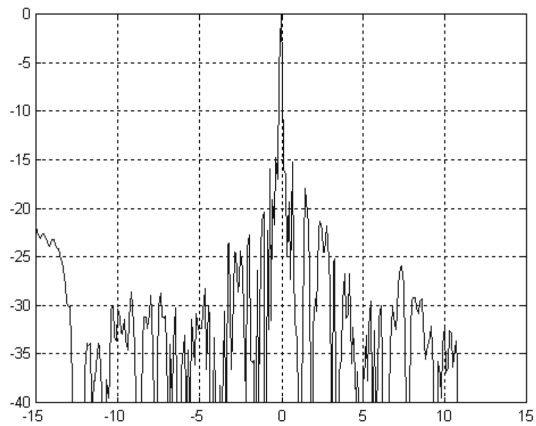

Figure 4. Measured beampattern for prototype one dimensional array.

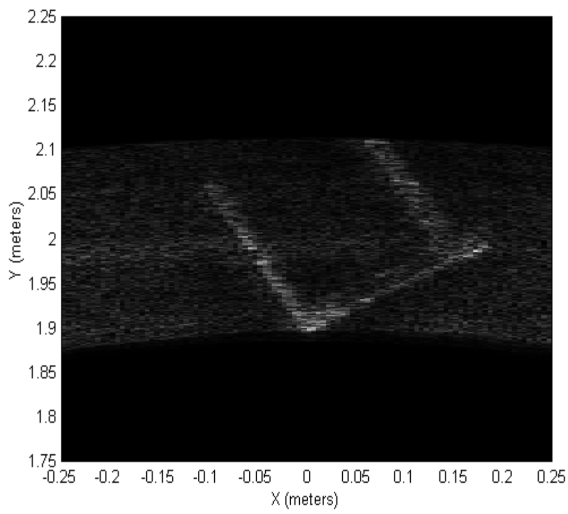

Figure 5. Acoustic image of cinder block suspended vertically in the Acoustic Test Facility. The array is at the bottom looking up along the y axis .

Experiments were conducted in the NUWC ATF to image various targets with the 32 element sparse line array. The targets were illuminated with a bistatic projector mounted 25 cm below the center of the array, perpendicular to the line of the array with a source level of 192 db re V./µ*Pa* at a range of 1.86 meters. Simple targets consisted of a 10 cm. stainless steel sphere and a 23 x 36 x 0.6 cm aluminum plate. A 19 x 19 x 40 cm. cinder block was submerged to provide an interesting more complex target. The dynamic range of the peak target highlights was approximately 40db. This was observed when comparing the level of the peak specular highlight from the aluminum plate at broadside with that of the plate rotated 45 degrees. Figures 5 show an example image from the cinder block at a 30 degree orientation, with optimized shading. The image dimensions are 0.5 m. x 0.5 m. The projector is located at bottom looking up. In this image three sides of the block appear to be imaged. The two solid cinder block walls are the thicker parallel sides. The voids are ported on the remaining face and allow the far wall to be imaged.

5. RESULTS AND CONCLUSION

The 32 element broadband sparse line demonstrated that this is a viable approach to follow for the development of a high resolution imaging sonar. The image shown in figure 5 is a positive result for the first prototype using this technology.

For broadside target orientation, large specular highlights dominated the image. Returns from other highlights were swamped by high sidelobe level. An example is the aluminum plate and the sphere. Highlights delineating the edges of the target were masked by the principle specular highlight. The simplest solution would be to illuminate the targets with a transmit beam with the dimensions of one image pixel. Because this sonar is for a moving diver, a frame update rate of 4 frames/sec is required. For targets at a range of 3 meters, the round-trip travel time only allows 60 pings per frame to construct an image of a 3 dimensional volume. For each ping, therefore, at least 166-sq. cm. cross-section needs to be imaged. This area would be covered by at least 64 pixels. A large specular highlight would therefore cause blooming over this pixel area. Where specular highlights occur is less predictable because the target is illuminated bistatically. Some of this problem could be solved with coded wideband transmit waveforms.

The experimental beampattern of figure 4 demonstrates that the sidelobes can be controlled by optimization over steering angles of 0.25° to 5°. Beyond the optimization range, the sidelobe level naturally decays to a minimal level out to ±12°. Limiting the transmit pulse beamwidth to 15º should therefore allow imaging without interference from grating lobes. Optimizing the shading at a given range (nearfield) provided sidelobe improvement but also shifted some of the interfering sidelobe structure into other range planes.

Square sparse planar arrays, 10-cm. and 20-cm, are in the fabrication stages by Tetrad Corp. with testing planned for the 3rd and 4th quarters of CY 2000.

6. ACKNOWLEDGEMENTS

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