

Composite Curved Linear Array for Sonar Imaging: Construction, Testing, and Comparison to FEM Simulations

C. Desilets¹, M. Callahan³, G. Hayward⁴, C. Maclean⁵, B. Mukherjee⁶,
V. Murray⁵, L. Nikodym², B. Pazol³, S. Sherrit⁶, G. Wojcik²

¹Ultrix Corporation 1215 Highland Drive, Edmonds, WA 98020

²Weidlinger Associates, 4410 El Camino Real, Suite 110, Los Altos, CA 94022

³Materials Systems Inc., 521 Great Road, Littleton, MA 01460

⁴University of Strathclyde, 204 George Street, Glasgow, G1 1XW, Scotland, UK

⁵UDI-Fugro, Denmore Road, Aberdeen, AB2 8JW, Scotland, UK

⁶Royal Military College, Kingston, Ontario K7K 5L0, Canada

ABSTRACT

The design, construction, performance, and comparison to FEM simulation of a broadband 375 kHz, 100 element, composite based, 115 mm radius curved receive array is described. This array was designed for use in a forward-looking, mine-hunting application with 60, 1.5° beams scanning a 90° sector. A 150° sector can be scanned with beamwidths widening beyond the center 90°. The bandwidth was desired to be 250 kHz, centered at 375 kHz. This array was demonstrated using an imaging system constructed by UDI-Fugro as part of a TTCP collaboration. The array was designed by Ultrix Corporation supported by FEM modeling at Weidlinger Associates and the University of Strathclyde. The array was constructed by Materials Systems Inc. (MSI) using their proprietary injection-molded composite technology and was tested by UDI-Fugro. Materials characterization was conducted at the Royal Military College of Canada.

The details of the final array design are described including the final composite microstructure, choice of composite filler, matching layer material and dicing pattern, and kerf filler. Array parameters achieved include 330 kHz center frequency, 245 kHz bandwidth, element acceptance angle from 62° at 250 kHz to 48° at 500 kHz, and sensitivity of -193 dB re 1V/uPa. FEM simulations showed excellent correspondence in predicting element electrical impedance.

INTRODUCTION

A mine counter-measures (MCM) array development team was formed in 1994 as part of

a Naval Technical Cooperation Program (TTCP) for the purpose of developing advanced sonar array designs, and in particular, obtaining broad bandwidth, high sensitivity operation. Team tasks include identifying a practical MCM application which would benefit from advanced composite arrays, designing an array(s) to meet that application, simulating the design of these arrays using an advanced time-domain finite element code developed by Weidlinger Associates, developing composite materials and array structures to improve array performance parameters, and building and testing feasibility array structures and prototype arrays.

Following a review of potential undersea imaging applications, a particular forward-looking, slant beam application was selected. A trade study was conducted by team members for system and array designs that would meet the system requirements for a minimum 90° scan sector and a minimum number of channels that would fit inside a 235 mm wide footprint. A curved array (Figure 1) solution was adopted over a phased array, since it places less stringent requirements on the element acceptance angle and required system delays. The array requirements are listed in Table 1.



Figure 1: Photograph of the Curved Array.

Table 1: Array Requirements

Center Frequency	375 kHz
Bandwidth	250 kHz
Array Envelope	235 mm wide x 150 mm deep
Beamwidth	1.5° at 500 kHz
Vertical Beamwidth	15° at 500 kHz
Scan Sector with Full Beamwidth	90°

The requirement for 1.5° beams at 500 kHz yields a 115 mm aperture. The pitch of the array was chosen to be one wavelength at the maximum frequency, or 3 mm at 500 kHz, from grating lobe considerations. Assuming that the maximum acceptance angle that can be obtained in an array of one wavelength pitch is $\pm 30^\circ$, the minimum radius of a curved array with a 115 mm aperture is 115 mm from simple geometry. Achieving a 90° sector using a full 115 mm aperture over the entire sector requires using a 150° curved array. The length of this array is 300 mm, which yields 100 elements on a 3 mm pitch. The active length of the array is 120 mm, which yields 40 active elements for any one scan line. With this pitch, there are 60 scan lines in the 90° sector separated by 1.5°, matching the beamwidth parameter quite nicely. The desired 15° vertical beamwidth at 500 kHz is obtained using an elevational aperture of 11.5 mm. The length of this 150°, 115 mm radius curved array projected onto the azimuthal axis is 232 mm, meeting the space requirement. A main issue with the use of this curved array was achieving the theoretical 30° acceptance angle in a composite array structure which can withstand some hydrostatic pressure, and will be discussed further.

TTCP team members at UDI-Fugro were also chartered to develop a system testbed for demonstrating this array. In the last year, a non-real time digital beamformer was built that would not only switch between elements to slide the active aperture around the array, but also provide focusing for near-field imaging. This system was used with the curved receiver array described, and a single element curved transmitter in imaging tests.

COMPOSITE AND ARRAY DESIGN

The piezoelectric material used in the array was a 1-3 composite of PZT ceramic in a polyurethane matrix. 1-3 composites were chosen for the enhanced electro-mechanical coupling constant and lower acoustic impedance, as reported widely in the literature[1]. Since MSI has developed an injection-molded composite technology which is expected to lower the manufacturing cost of arrays, the design of the composite was adjusted to fit MSI's capability in fine-scale composites. Several designs were considered based on some rules of thumb developed at the University of Strathclyde; it was desired to have at least 5 ceramic pillars in azimuth per element, and a 50% volume fraction ratio. Tooling issues at that point in time limited the composite parameters to 3 pillars in azimuth and a 40% volume fraction. Acceptable performance was obtained with this configuration, although more work will be conducted to study the effects of this relatively coarse composite microstructure. The composite pillars were chosen to be 0.63 mm square and regularly spaced on a 1 mm pitch, leaving 3 pillars in azimuth and 12 pillars in elevation under each element electrode. The element electrodes were separated by the 0.37 mm spacing between adjacent pillars as can be seen in Figure 2.

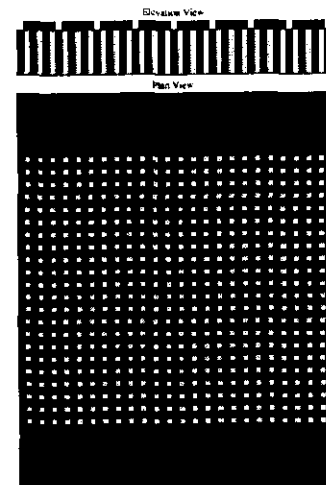


Figure 2: Schematic of Final Array Geometry.

Maximum sensitivity of a transducer is obtained by operating at resonance; many sonar devices have large bandwidths, obtained by operating below resonance and, sacrificing sensitivity as a result. Following the usual practice in commercial applications, this array was designed to operate at resonance for maximum sensitivity and to use a matching layer to achieve up to one octave of bandwidth[2]. A single, continuous matching layer was designed to test the properties of the matching layer with the composite, and validate the effective composite parameters used in the simple 1D model and a sample module. It was expected that excellent transducer characteristics would be obtained, including smooth bandshape response and the required bandwidth using a matching layer of 4.24 MRayl. This was demonstrated in an early prototype module.

However, experience has shown that a continuous matching layer will limit the directivity pattern below the theoretical value, $\pm 30^\circ$ in this case. As expected, very low acceptance was observed on the array module with continuous matching layer. Hence, a diced matching layer design was generated to solve this issue based on experience with medical arrays. Dicing the matching layer, however, increased the complexity of the design substantially, since a kerf filling material would have to be found that not only keeps the elements decoupled to obtain the desired acceptance angle, but survive in a high pressure environment. In addition, the modes excited in the matching layer are considerably more complex since lateral modes in the diced matching layer will strongly couple to the preferred mode. Using simple coupled mode theory, which was shown to have good correlation to the lowest order symmetric Lamb wave[3], an effective velocity and impedance was generated to use in the design simulation tools. The matching layer structure was thoroughly simulated using the PZFlex FEM tool and compared to experimental results[4]. Within the range of matching layer aspect ratios considered, the FEM simulation showed that the effective velocity of the layer was identical to the asymptotic value obtained from coupled mode and Lamb wave theory over the large range of aspect ratios[4]. This was a somewhat surprising result and warrants further study. The matching layer is 1.6 mm thick and diced completely through to the composite on a 3 mm pitch

corresponding to the major element pitch, as can be seen in Figure 2.

Having generated the basic composite and matching layer design, the remaining key issues were the backing material and kerf filler materials. Since this array operates in receive mode only with long time delays between transmit and receive, almost any mechanically rigid backing will suffice. A simple low acoustic impedance mix of urethane and microballoons was used. The kerf filler was an entirely different story. Difficulties in measuring good properties of lossy polymers precluded using a simulation approach to this problem; consequently, many sample modules were constructed with various lossy composite filler and kerf filler materials in a totally empirical approach. These are described in the next section.

CONSTRUCTION PROGRAM AND TEST RESULTS

Several 7 element array modules were built and tested using a relatively stiff Shore D 80 polyurethane composite filler material. Several surprising results were obtained from these samples. While the composite by itself showed only very minor lateral and stopband resonances near the design passband, applying the matching layer caused many deleterious resonances to increase in strength and significantly reduce the usable bandwidth. In both the continuous and diced matching layer cases, a strong resonance at 350 kHz provided unacceptable passband ripple. In addition, the matching layer resonance was found to be considerably lower in frequency than predicted by 1D model using effective velocities and impedances. This phenomenon can most easily be seen in Figure 3, which shows the electrical impedance of one element in a diced matching layer array module. Numerous and regularly spaced resonances are shown, in addition to coupled ceramic and matching layer resonances. Also, as expected, the acceptance angle was below $\pm 20^\circ$ for the continuous matching layer case as expected. However, the acceptance angle for the diced matching layer case showed little improvement, which was not expected.

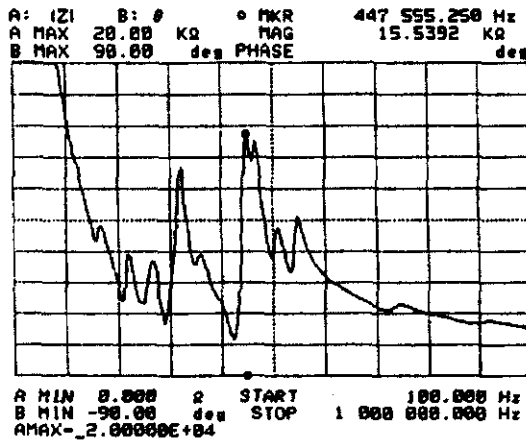


Figure 3: Air-loaded Electrical Impedance Magnitude of One Test Array Element Showing Electrical Harmonics.

After some consideration, it was agreed that these resonances were the result of lateral mode harmonics in the overall array module structure, most of which resulted from resonances in the 12 pillar, elevation direction. This became evident as the array manufacturing processes were steadily improved; the resonances were clearly regularly spaced harmonics of a low frequency fundamental, which corresponded roughly to the elevation dimension. These modes were also seen on a FEM generated impedance curve. It was concluded that a lossier composite filler material would need to be employed in order to damp out these resonances. Consequently, a series of samples were constructed using softer polyurethane fillers, including Shore D 70, Shore D 75, and Shore D 65, as well as some microballoon/urethane mixtures.

The microballoons had very little effect on dampening these resonances; softer fillers helped considerably, but not to the extent needed. Manufacturing concerns precluded using even softer materials than the gummy

Shore D 65 urethane. At this point, the remaining avenue left was to increase the number of pillars in the elevation direction, still leaving only 12 electroded and electrically active. This lowered the fundamental elevational acoustic resonance and allowed a greater damping length to come into play for the harmful elevational harmonics. It was easy from a manufacturing standpoint to generate 22 pillars in elevation (12 active - see Figure 2); consequently, a final module was built in this configuration using the Shore D 65 filler material. The air-loaded and water-loaded electrical impedance of one element of this module (#14) is shown in Figure 4. These curves show little evidence of deleterious elevational harmonics and promised acceptable array performance parameters.

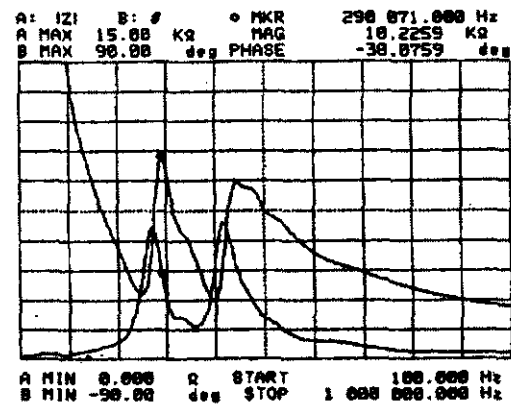


Figure 4: Air-Loaded Electrical Impedance of Array Module 14 Showing Little Evidence of Electrical Harmonics.

Two-way impulse and frequency response characteristics were generated for this array module with sealed air kerfs (Figure 5). The bandwidth is a less than desired (320-425 kHz), although impressive for a resonant sonar array. The two-way acceptance angle is $\pm 32^\circ$ which is practically the theoretical limit.

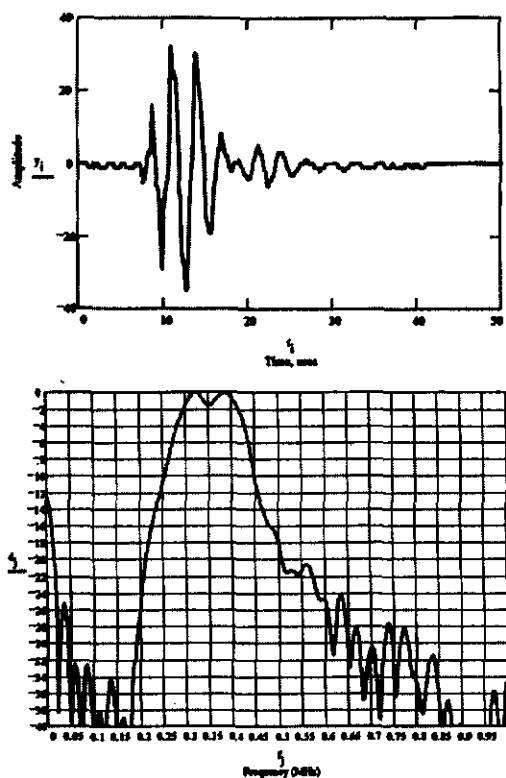


Figure 5: Time and Frequency Response of Element of Module 14 with Air-Filled Kerfs.

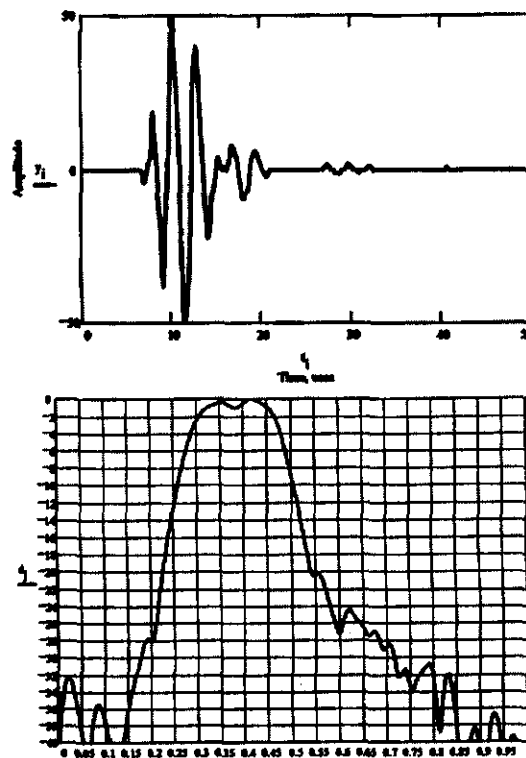


Figure 6: Time and Frequency Response of Element of Module 14 with Encapsulant-Filled Kerfs.

However, sealed air gaps are unacceptable in a sonar array due to the high pressure undersea environment. This array module (#14) was kerf-filled with a standard sonar encapsulant urethane and retested. The bandwidth improved to 275-485 kHz (Figure 6), but the acceptance angle fell to only $\pm 22^\circ$ (Figure 7). This configuration was used in building the first two full 100 element curved arrays, while further modules were built to test additional kerf filler materials. No substantial improvement in the acceptance angle was noted using a variety of soft, lossy materials during tests conducted over the last few months. This issue will be studied further in the next phase of the program. Clearly the need for accurate material parameters for lossy polymers is needed as well in order to simulate this important parameter in FEM calculations.

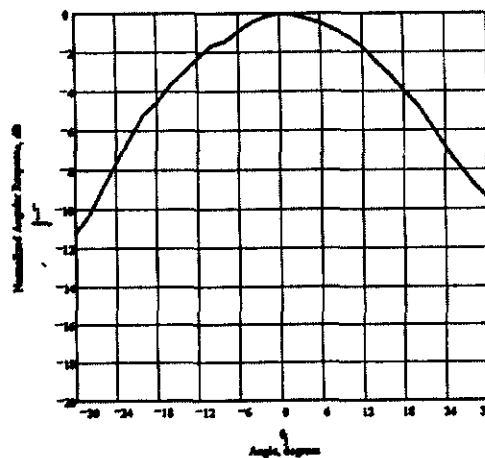


Figure 7: Broadband Round Trip Angular Response of Element of Module 14 with Filled Kerfs.

A full curved array prototype was constructed with all 100 elements active, sealed for undersea use, and shipped to UDI-Fugro for calibrated array receive sensitivity and directivity tests, and incorporation into the demonstration imaging system. This particular array was slightly off radius on each end of the array, which led to phase errors in the beamforming process away from the middle half of the array. A second array has been constructed recently which should correct this problem, and will be undergoing tests in the near future. The following table summarizes the test results:

Table 2: Array Test Results

Max Receiver Sensitivity	-193 dB re 1V/ μ Pa
-3 dB Bandwidth	208-453 kHz (74%)
Beamwidth, 250 kHz	$\pm 31^\circ$
Beamwidth, 375 kHz	$\pm 30.5^\circ$
Beamwidth, 500 kHz	$\pm 24^\circ$

The sensitivity of this array is comparable to narrowband arrays currently in use, but the 74% bandwidth will allow for several broadband imaging modes to be employed using this array. The element beamwidth is acceptable for most of the passband, falling off to 24° at 500 kHz. The second array with improved mechanical phase uniformity should prove quite useful in demonstrating broadband imaging modalities.

SUMMARY

A 100 element curved sonar receive array was designed and built using 1-3 composite technology in order to demonstrate sensitive, broadband operation. This array employed state-of-the-art injection molded piezoelectric composites, and a diced matching layer to maximize sensitivity, bandwidth, and element angular response. While FEM modeling was limited in scope, good agreement was achieved between simulation and experiment in several respects. Initial field tests were conducted this summer using the UDI-Fugro beamformer, and images over the full frequency range were

obtained. The system currently has limited dynamic range, transmit power, and high sidelobe levels which will need to be improved before additional field test are run. These issues will be addressed in the next phase of the program.

A second prototype array has been built which is expected to have corrected some overall curvature issues which led to phase errors in imaging reconstruction. This second prototype array also has coarse apodization in the elevational direction achieved by electroding the middle 3 x 10 pillars in elevation and extending the electrode pattern 1 x 3 additional pillars on both ends. Simulation of this pattern shows that the sidelobes should be reduced from -12 to -20 dB while maintaining the 15° beamwidth (at 500 kHz). This second array will be undergoing tests this fall.

ACKNOWLEDGEMENTS

This work was supported by the Office of Naval Research (USA) and the Defense Research Agency (UK).

REFERENCES

- [1] W.A. Smith and B.A. Auld, "Modeling 1-3 Composite Piezoelectrics: Thickness-Mode Oscillations", *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 38, pp. 40-47, 1991.
- [2] C.S. Desilets, J.D. Fraser, and G.S. Kino, "The Design of Efficient, Broad-Band Piezoelectric Transducers", *IEEE Transactions on Sonics and Ultrasonics*, SU-25, pp. 115-125, 1978.
- [3] S. Ayter, "Transmission Line Modeling for Array Transducer Elements", *Proceedings of the 1990 IEEE Ultrasonics Symposium*, pp. 791-794, 1990.
- [4] G. Wojcik, C. Desilets, L. Nikodym, D. Vaughan, N. Abboud, J. Mould, "Computer Modeling of Diced Matching Layers", *Proceedings of the 1996 IEEE Ultrasonics Symposium*, pp. 1503-1508, 1996.