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Recent Advances in 1-3 Piezoelectric Polymer Composite Transducer Technology for AUV/UUV Acoustic Imaging Applications

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Abstract. Over the past 5 years, the use of 1-3 piezoelectric polymer composite has been studied under various U.S. Navy-funded transducer research programs. As a transduction material, the 1-3 piezoelectric composite offers many advantages for autonomous undersea vehicles/unmanned undersea vehicle (AUV/UUV) imaging array construction. Broad bandwidth, high transmit/receive response, low cost of fabrication, mechanical ruggedness, and the ability to form conformal shapes make this material both a unique and intriguing medium for the sonar transducer designer. The 1-3 piezocomposite panels are comprised of several piezoceramic rods aligned vertically through the panel's thickness with each rod surrounded with a specific polymer epoxy. Volume fractions of ceramic to polymer can vary up to 50% with panel thickness ranging between fractions of a millimeter (2 to 4 MHz) to 25 millimeters (50 to 70 kHz). This article will elucidate the application of this unique material to a variety of practical transducer designs and describe some of the recent device demonstrations along with measured performance data.

Keywords: 1-3 piezocomposite, imaging arrays, conformal arrays, unmanned vehicles

1. Introduction

The initial demonstration of the 1-3 piezocomposite panel as a viable transduction medium [1] was conducted at the Materials Research Laboratory of The Pennsylvania State University around 1977 under basic research funding support from the Office of Naval Research. The active panels were constructed primarily by dicing and backfilling solid ceramic blocks, making the 1-3 composite technology well suited for small, high-frequency (>1 MHz) biomedical transducer arrays [2]. Thus, the first commercialization of the material by the biomedical imaging community began in early 1980. In early 1990, Materials Systems Inc. (MSI) perfected a ceramic injection molding process [3] by mixing ceramic powder with a wax binder. Similar to injection molding of plastics, the process enabled larger 1-3 piezocomposite panels to be formed more cost effectively. Throughout the 1990s, MSI's injection-molded 1-3 piezoceramic has steadily gained acceptance as a viable transducer material in the U.S. and U.K. Navies, as well as in the commercial sectors in the United States [4, 5], Japan, and Europe.

2. Doubly Curved Two-Dimensional Conformal Array Development

This section describes a hardware demonstration that illuminates the unique advantages 1-3 piezocomposite affords in the fabrication of conformal two-dimensional arrays. The development of doubly curved acoustic arrays for UUV applications was the focus of this study. The sensors employed a 1-3 piezoceramic thermoplastic composite that is conformable at elevated temperatures and capable of deep ocean operation.

The thermoplastic epoxy phase of the composite allows the active panel to be shaped to any reasonable specific vehicle geometry. For the current receiver application, low-profile (<1.0 mm) coaxial cables embedded within the composite panels provide addressing

Fig. 1. Two-dimensional array suite for new AUV/UUV concept.

between the acoustic array elements and the processing electronics [6]. It is noted that the array fabrication approach is applicable for both transmit and receive operation.

Figure 1 shows a computer-generated version of two conformal array concepts that were realized through the fabrication process described herein. The actual arrays are shown in Fig. 2. Although the array in Fig. 2 is a mock-up for concept demonstration, the measured results for selected array elements clearly show the merits of the 1-3 piezocomposite and the fabrication techniques employed [7, 8].

The smaller transition array consisted of one active and eleven inactive array segments. The array segments before curving are shown in Fig. 3. The array segments were warmed to 65°C and curved using a pair of aluminum mold halves. This array featured a very tight bend radius toward the leading edge, as shown in Fig. 4.

Key to the conformal array fabrication is the Mercator's projection of the conformal aperture on to a flat plane. This facilitates the application of the plated electrodes that will ultimately make electrical connection to the embedded element cabling within the 1-3 piezocomposite panels as depicted in Figs. 5, 6, and 7.

For this receive array demonstration, low profile (<1.0 mm) coaxial cables were used. The wires are laid at the mid-plane of the panel and exit out the edge of the panel for convenient routing to the electronics located interior to the vehicle.

The opposite ends exit the broad face of the panel at the intended element locations. After backfilling and Blanchard grinding the array panels, the copper cross sections of each wire are exposed at the surface of the panel, as shown in Fig. 6 and again in close-up in Fig. 7.

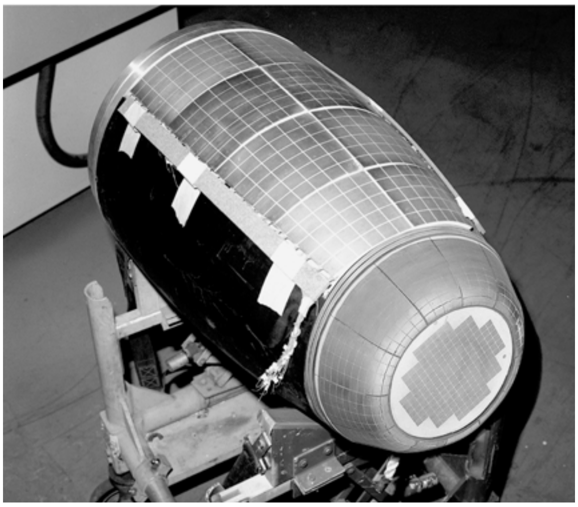

Fig. 2. Actual constructed arrays before final encapsulation.

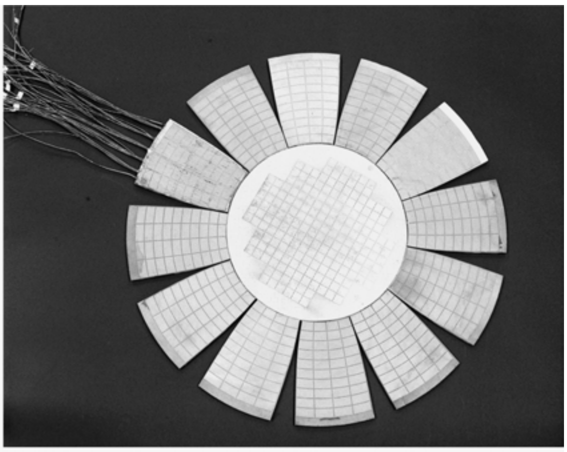

Fig. 3. Transition region array (before curving).

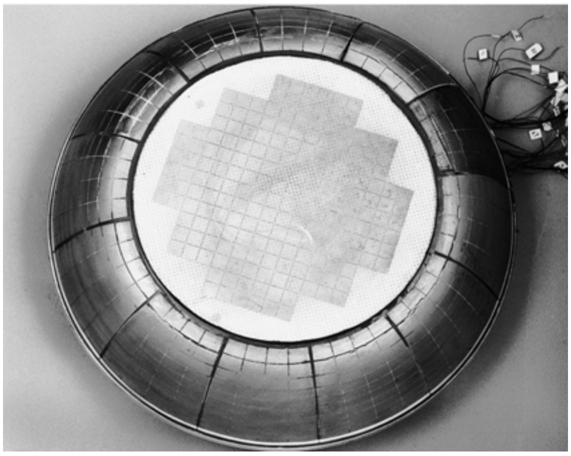

Fig. 4. Transition region array (after curving).

Figure 8 is a photograph of the eight array panels after the copper electrodes were electroplated and photo-etched. Copper appears to be an excellent choice for an electrode material. It has been used for both higher frequency, and transmit, piezocomposite transducer designs. Also it is noted that the current technique eliminates the need for attaching wires externally with solder or conductive epoxy. Both the electrical and mechanical attachments are made in the plating step.

The vehicle section was warmed overnight to approximately 65°C along with the eight copper-plated array panels. In this case the panels were curved using the vehicle section, a continuous doubly curved spacer that simulated the presence of the intended backing layer, and ordinary tie-down straps. Three rows of tongue depressors were used as stress risers along the edges and central seam where more stress was required to curve the panels. Three or four tongue depressors were stacked vertically under the strap to keep the panel edges down. Figure 9 shows the array panels in the oven during the final stages of thermoforming. The curving and joining of the panels were greatly facilitated by using specifically designed conformal tools constructed by a stereo-lithography apparatus (SLA). These tools were also critical to the application of the absorptive backing and acoustic window.

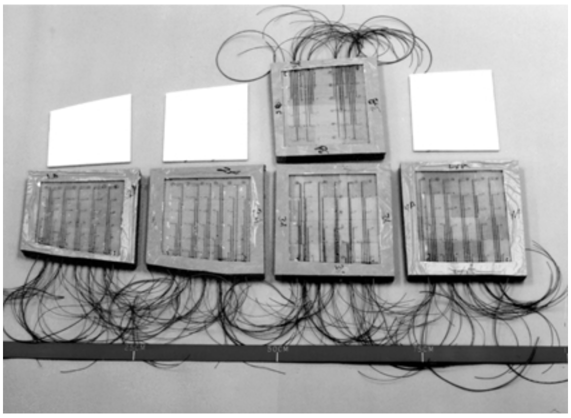

Fig. 5. Side-looking array showing active and dummy panels (before curving).

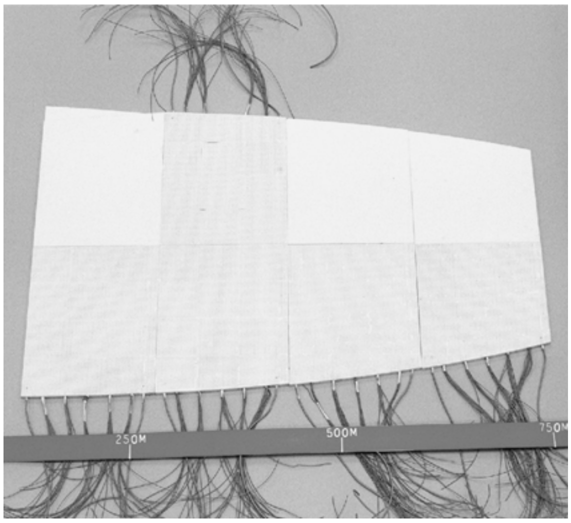

Fig. 6. Side-looking array panels after molding and grinding step (before curving).

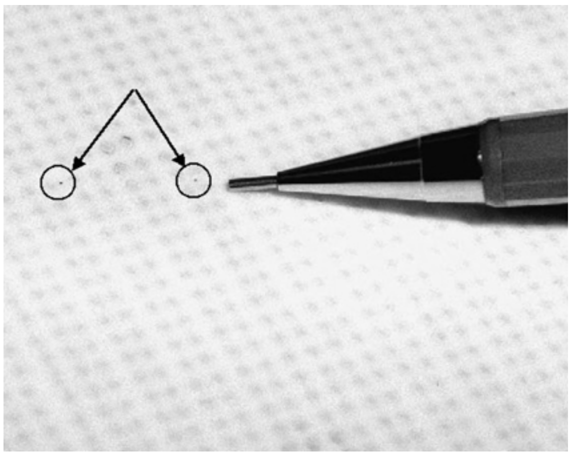

Fig. 7. Closeup of two 0.25 mm diameter cable end cross sections that will make electrical connection to a plated element electrode.

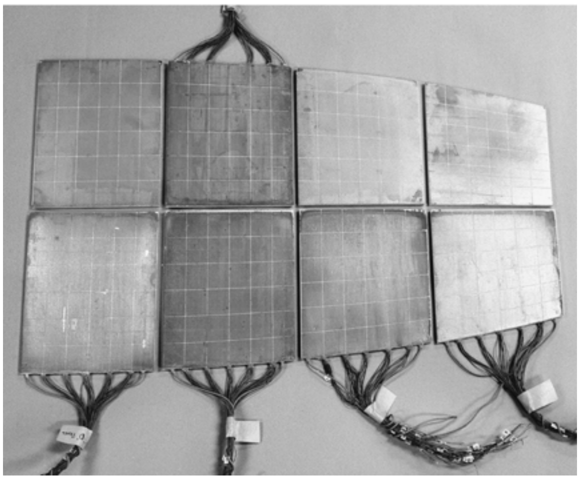

Fig. 8. Side-looking array after element electrodes have been deposited via copper electroplating and photo-etching.

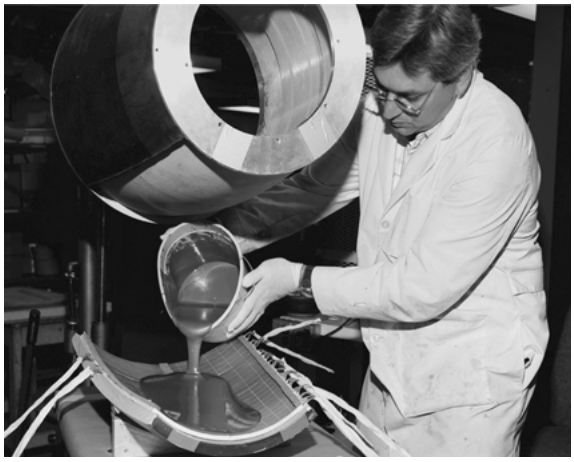

Fig. 10. Application of the absorptive backing (dispensing).

For the application of the absorptive backing, two conformal SLA tools were used. One simulated the acoustic window by providing a continuous standoff distance (approximately 3 mm) between the outer array surface and the outer shell surface. The other SLA tool provided a means to mold the acoustic window and was used to encapsulate both the active and inactive portions of the vehicle.

With three-quarters of the vehicle encapsulated, and one-quarter grit blasted, the backing was applied by lowering the vehicle section into the uncured mixture as shown in Figs. 10 and 11. The material was cured overnight at room temperature.

The backing (TECHTHANE-12 by Seaward International, Inc.) provides electrical and mechanical isolation from the shell. As a convenient two-part, room temperature cure mixture, it also provides a means of adhesion between the shell and active 1-3 piezocomposite array. The backing thickness was 12 mm.

The completed demonstration array suite is shown in Fig. 12 being lowered into the acoustic test tank for acoustic calibration. Figure 13 corresponds to a measured receiving voltage response for a selected array element within the larger side-looking array. The frequency parameter spans the range 10 to 100 kHz. Note the well-behaved broadband response that the 1-3 piezocomposite construct provides.

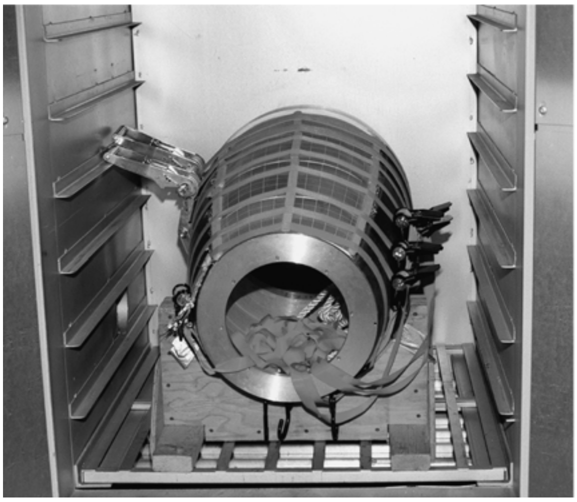

Fig. 9. Array panels at final stages of thermoforming.

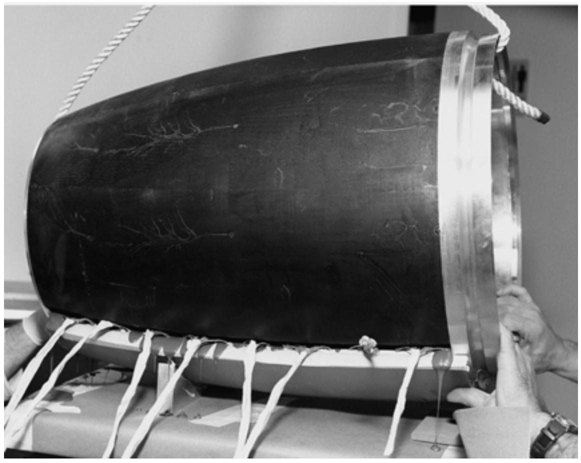

Fig. 11. Application of the absorptive backing (molding).

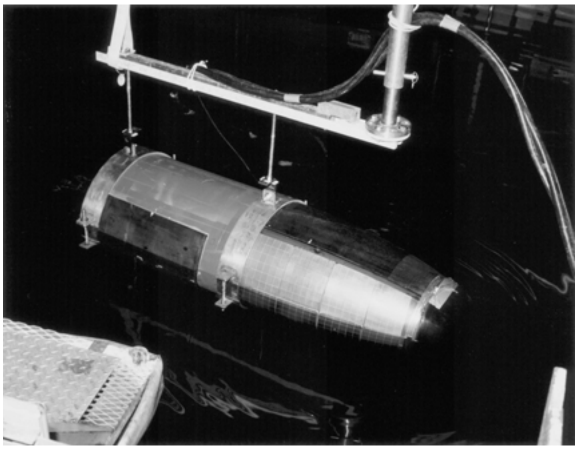

Fig. 12. Completed conformal arrays.

Figure 14 shows a measured roll-plane receive beam pattern for one of the elements in the side-looking array. Again the low lateral response of the 1-3 piezocomposite is noted in the spatial response.

3. Conical Two-Dimensional Conformal Array Development

The purpose of this demonstration was to explore the feasibility of producing an electronically steerable, conical array that could help guide a high-speed underwater vehicle. Research in hydrodynamics and vehicle control indicates that conical shapes provide major enhancements in vehicle control during high-speed (∼150 knots) flight. As a starting point for this experimental exploration, the following geometry was chosen: 18.3 cm tall, with a base of 13.3 cm, and a 20° conical half-angle.

The 1-3 piezocomposite material provided the technological breakthrough needed to produce a rugged, broadband, acoustical imaging array that conformed to the desired vehicle shape.

The focus of this section is the fabrication of an octahedral approximation of a conical array. Similar to the doubly curved arrays described above, most of the design and tooling of the mechanical components of this experimental array were modeled using a computer-aided design (CAD) package and were subsequently fashioned using SLA.

The piezoelectric composite substrate thickness for this demonstration was 1.7 cm with a half-wave thickness resonance of approximately 86 kHz. For this study, the array was air backed.

Figure 15 shows the CAD model of the passive components that house the conical array. The array consists of eight active array segments, a nose tip, and a base. The array segments have a louvered array isolator component that organizes the 15 elements

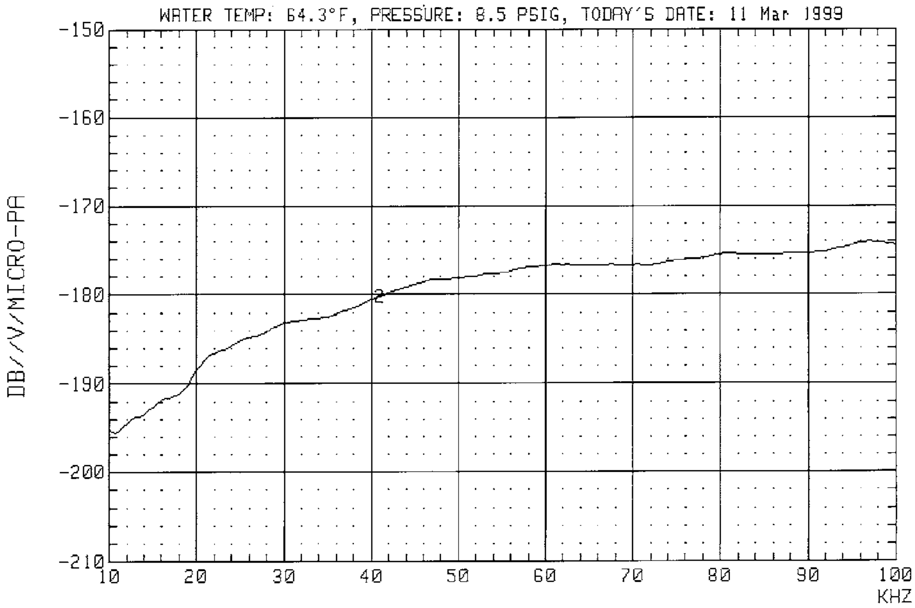

Fig. 13. Measured receiving voltage response for a single array element within the side-looking array shown in Fig. 12.

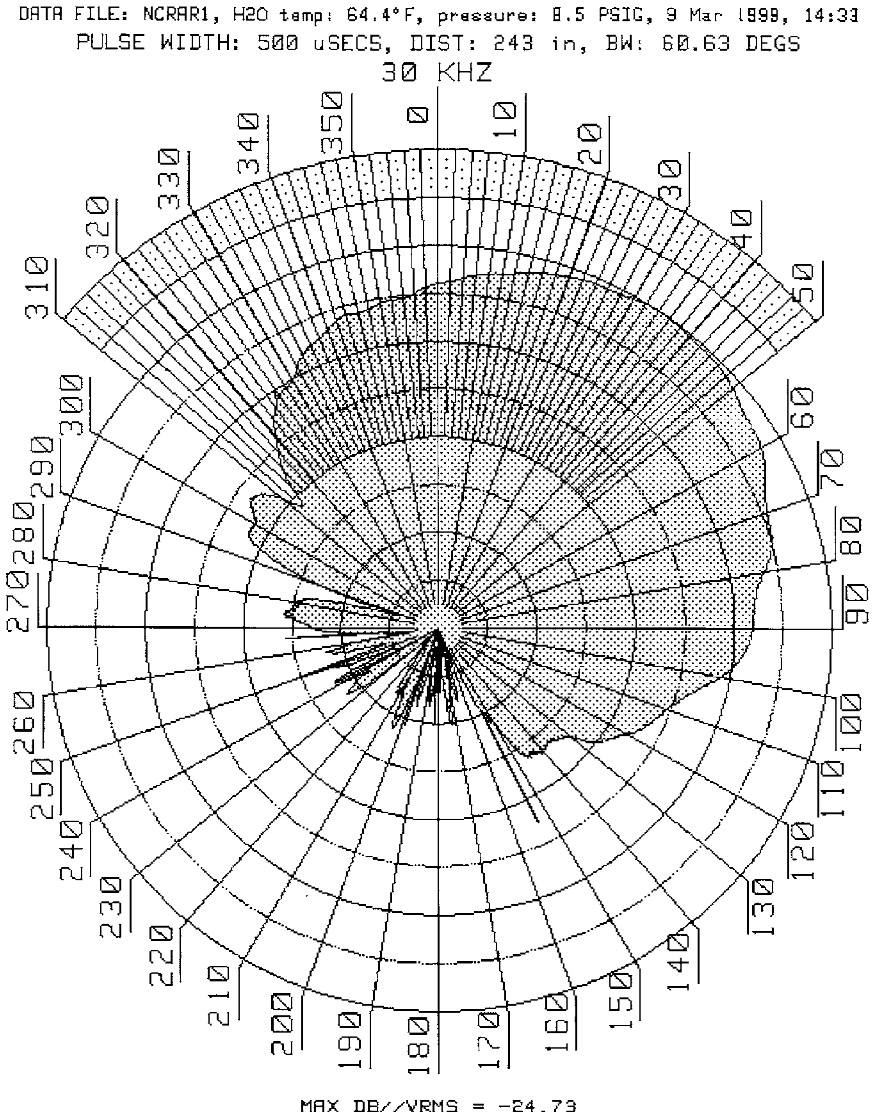

Fig. 14. Measured roll-plane receive beam pattern for side-looking array shown in Fig. 12.

within each array segment. The segments can be fashioned from a variety of viscoelastic materials to isolate array elements within the array segment and thus mitigate array element mechanical coupling.

Figure 16 shows three isolator components fashioned from different materials. They are noted in the figure caption.

Also shown in Fig. 16 (just right of center) is an injection-molded PZT ceramic pre-form prior to its installation into an array isolator.

For this feasibility study, the array isolators were constructed with MSI's standard Shore D80 epoxy micro-balloon, backfill material, which is preferred for operational ruggedness and lateral decoupling. Also, scanning laser vibrometer measurements indicate this construction provides adequate inter-element mechanical isolation over the frequency range of interest.

Lastly, the series of holes programmed along the long axes of the array isolators was originally intended for electrical cabling. Although the cabling was not required for this demonstration, these holes represent an intriguing feature for future array designs.

Fig. 15. CAD model of 120-element, conical, octahedral imaging array.

Fig. 16. Three array isolator materials: Shore A60 polyurethane with microballoons (left), Styrofoam (middle), and Shore D80 epoxy with microballoons (right).

Figure 17 shows a loaded array isolator. As can be seen, the array isolator louvers separate and organize the individual ceramic pre-forms. Similar to the doubly curved case, the ground wire (green, lower left) is installed prior to backfilling. Figure 18 shows a measured velocity distribution over the surface of a completed array segment when one of the center elements is driven at 45 kHz. As seen in the figure, most of the velocity distribution (lines of isovelocity) is concentrated over the element being driven with very little coupling to the adjacent elements.

When backfilling has been completed, the parts are machined to the specified geometry and then electroplated with copper to define the element electrodes. The sides of each array segment are beveled in such a way that they mate to each other as well as to the cone tip and the base to form the conical aperture.

Figure 19 shows four array segments before the positive lead wires have been attached. The plated surfaces facing outward were protected with cardboard to avoid tarnishing and other damage that could occur through handling.

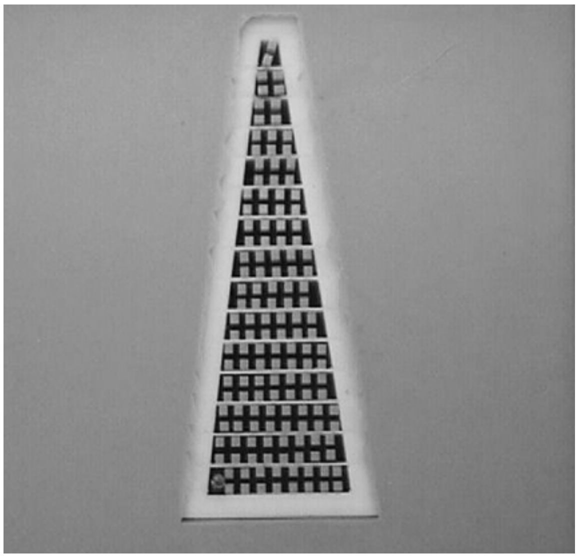

Fig. 17. Loaded array isolator.

Fig. 18. Laser vibrometer scan of 15-element array segment (element 8 at 45 kHz).

The positive leads for each of the 120 elements were inserted into conductive epoxy-filled holes before the epoxy cured. Figure 20 shows a close-up of an array segment that is ready for wire insertion. The controlled squeeze-out of conductive epoxy caused by the insertion of the wire into the hole provided electrical contact between the wire and the copper-plated element electrode.

The 4-hr pot-life of the room temperature-curing conductive epoxy (TRA-CON, Tra-Duct 2902) allowed the insertion of all 120 wires in one sitting.

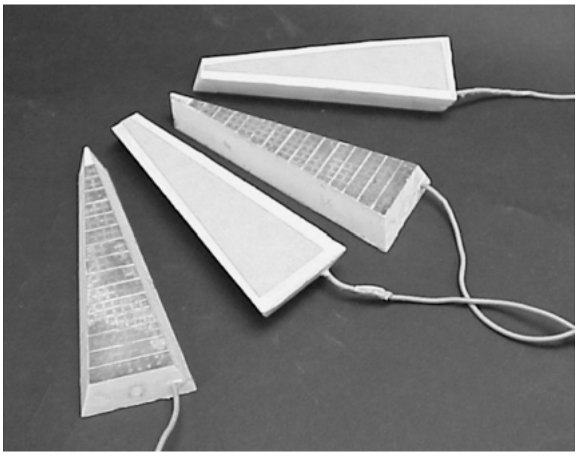

Fig. 19. Four array segments prior to positive lead attachment.

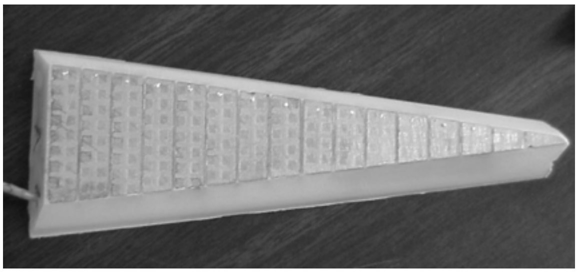

Fig. 20. Closeup of drilled and filled array segment ready for wire insertion.

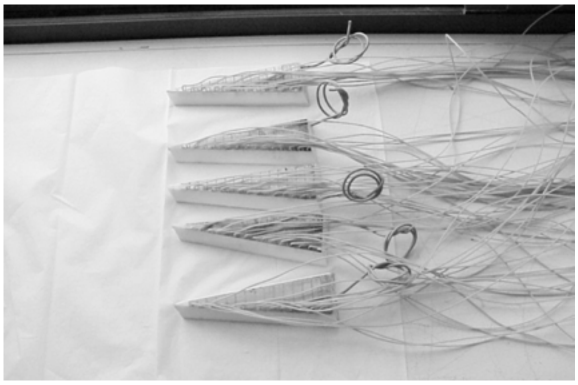

Fig. 21. Five of eight wired array segments comprising conical aperture.

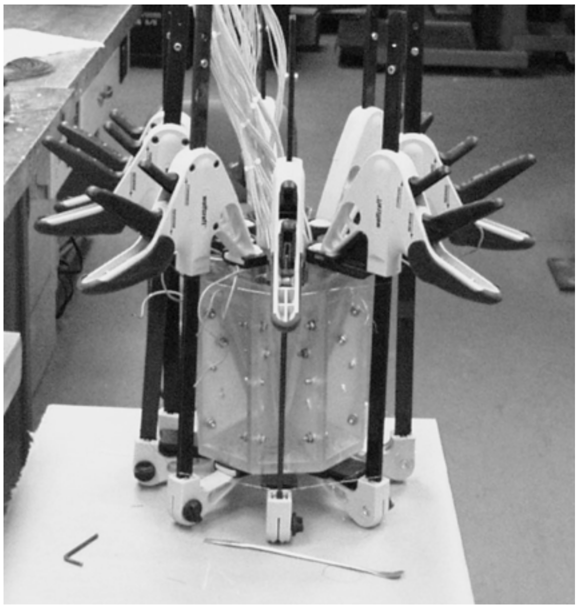

Fig. 22. Bonding eight array segments using SLA fixture.

The wire ends were prepared prior to the mixing and dispensing of the conductive epoxy. The preparation of the wires consisted of stripping the insulation off, twisting the strands tightly, and cutting them to a specific length. Figure 21 shows five wired array segments.

Because the individual positive electrodes on the inside surface of the cone were so close to each other, strips of Kapton tape (6 mm wide, not shown) were used as isolators between the array segments to prevent shorting between adjacent array elements.

Figure 22 shows the array segments being bonded together to form the octahedral conical sub-array. Armstrong A2 structural epoxy with micro-balloons (40% by volume) was applied to the side surfaces of each array segment before the segment was placed into the bonding fixture.

Eight woodworking clamps forced the array segments into the SLA bonding fixture. The micro-balloons thickened the epoxy, making the epoxy cure more quickly and less likely to run from the voids and imperfections between the mating surfaces. After the eight segments were bonded together, the subassembly was placed base down and the cone tip was attached using the same epoxy system.

Next, the wire leads (positive and negative) were routed through the base, and the same epoxy system was used to bond the base to the array subassembly. The addition of micro-balloons gave the adhesive

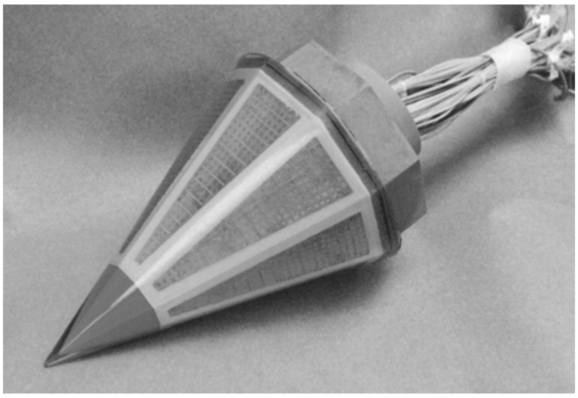

Fig. 23. Potted 120-element cone array ready for test.

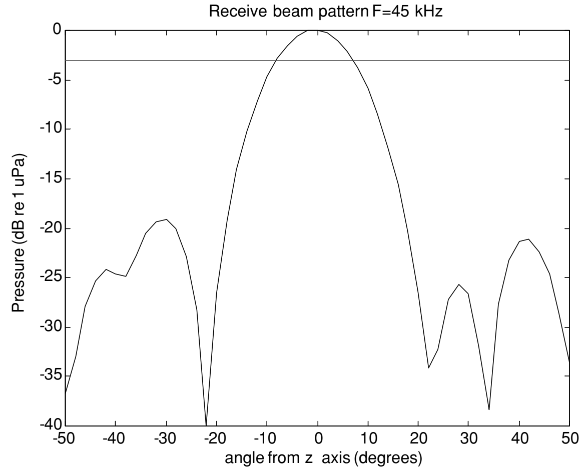

Fig. 25. Measured forward-looking beam pattern.

a putty-like consistency that mitigated any surface imperfections between mating halves. The finished cone is shown in Fig. 23.

The measured transmit voltage response for elements 6 through 10, is shown in Fig. 24. The frequency ranges from 30 to 80 kHz. Figure 25 shows a time delay beamformed boresight receive beam pattern taken at 45 kHz.

4. Conclusions

The 1-3 piezoelectric composite material enables a variety of unique conformal transducer array designs to be realized for underwater imaging applications. The prototype arrays, described in this article, demonstrate

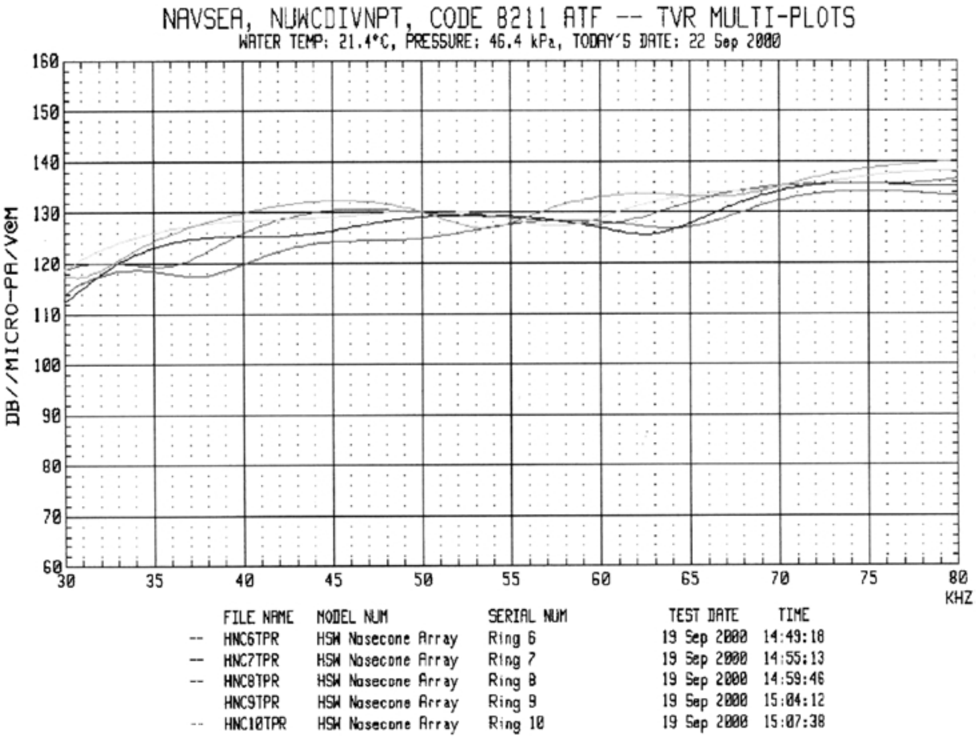

Fig. 24. Measured TVR for five rings of elements.

the utility of the 1-3 piezocomposite when it is used as an active substrate. The measured results indicate the wide operational bandwidth and spatial fidelity typical of 1-3 piezocomposite constructs.

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