Electroacoustic Evaluations of 1-3 Piezocomposite SonoPanel™ Materials

Thomas R. Howarth, *Member, IEEE*, and Robert Y. Ting

***Abstract*—An advanced configuration 1-3 piezocomposite, designated by its manufacturer as SonoPanel™, has been investigated for potential underwater acoustical applications. In-air electromechanical characteristics and in-water acoustical properties of the SonoPanel™ were experimentally examined. The in-air impedance measurement results showed the existence of parasitic modes in the composite panel in addition to the expected thickness mode. This modal behavior is identified to be related to the piezocomposite structure. In-water acoustical properties of the new 1-3 piezocomposite panels were investigated as a function of temperature, hydrostatic pressure, and frequency. The effect of underwater explosive shock on the acoustic responses showed no detrimental effects in mechanical structure or acoustical performance of the piezocomposite panel. Linearity with electrical drive level and hydrostatic pressure stability of the 1-3 piezocomposites also were established. These results suggest that the SonoPanel™ piezocomposite material is potentially useful for underwater acoustical applications, particularly in applications in which large area coverage is desired.**

I. Introduction

Piezoelectric ceramics such as lead-zirconate-titanate (PZT) compositions have been used in underwater transducer applications for many years. These bulk ceramics are dense, heavy and of limited size and shape so that they are rather difficult to apply for large area coverage. For applications involving the coverage of a large surface, the transducers function in a hydrostatic mode, which means they are needed to be operational over an extended frequency band as opposed to a purely resonant device that operates in a pure "33" mode. The piezoelectric voltage coefficient in this mode (g_h) is related to the longitudinal and transverse direction coefficients through the following relationship:

$$g_h = g_{33} + g_{32} + g_{31}. \quad (1)$$

Unfortunately, in PZT ceramics both the coefficients g_{31} and g_{32} have magnitudes nearly equal to half that of g_{33} but are of a different sign [1]. This results in a very small g_h, or a very poor hydrostatic mode response [2]. Therefore, new materials with improved hydrostatic piezoelectric properties that are also light, flexible, and/or conformal are being sought. In addition, it is highly desirable that the new materials be processed at low cost to form large sheets for applications that demand the coverage of large area surfaces.

Manuscript received March 11, 1999; accepted October 6, 1999. This work was supported by the Defense Advanced Research Projects Agency (DARPA).

T. R. Howarth is with the Naval Research Laboratory, Washington, DC 20375-5350

R. Y. Ting is with the Department of Mechanical, Materials and Aerospace Engineering, University of Central Florida, Orlando, FL 32816-2450.

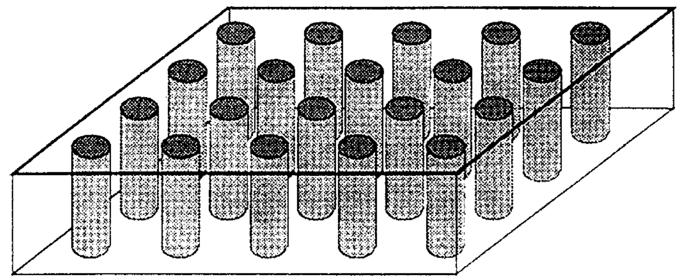

Fig. 1. Schematic representation of a 1-3 piezocomposite material structure.

Research work pioneered at the Pennsylvania State University's Materials Research Laboratory has led to the development of a large variety of piezoelectric composite materials that consist of a ceramic and a polymeric phase with different connectivities [3]. The self-connectivity in one, two, or three dimensions in a composite is designated as "1, 2, or 3". Therefore, a piezocomposite consisting of thin piezoelectric ceramic rods aligned in parallel and embedded in a polymeric resin matrix is called a "1-3" composite. The ceramic rods are connected in only one direction, the poled direction of the material, with a connectivity of "1". However, the polymer phase is connected in all three dimensions, with a connectivity of "3". Fig. 1 shows a schematic of the 1-3 piezocomposite concept. In recent years this type of piezoelectric composite material has been investigated for applications in large-area hydrophones and as high-frequency underwater imaging transducers [4], [5].

In this paper, the results of an investigation on a specific 1-3 piezocomposite material configuration is reported and discussed. The configuration is a trademarked product named the SonoPanel™as developed and manufactured by Material Systems, Inc. (MSI), Littleton, MA [6]. The in-air characteristics of these materials, as well as their in-water acoustical properties, have been measured. The effects of temperature, hydrostatic pressure, and underwater explosive shock on the acoustic performance of the materials as an underwater transducer were examined.

II. SonoPanel™Configuration

Conventional 1-3 piezocomposite materials typically have been fabricated by using a dice-and-fill method,

0885–3010/$10.00 © 2000 IEEE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUL 2000**	2. REPORT TYPE	3. DATES COVERED **00-07-2000 to 00-07-2000**

4. TITLE AND SUBTITLE **Electroacoustic Evaluations of 1-3 Piezocomposite SonoPanel Materials**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue SW,Washington,DC,20375-5350**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

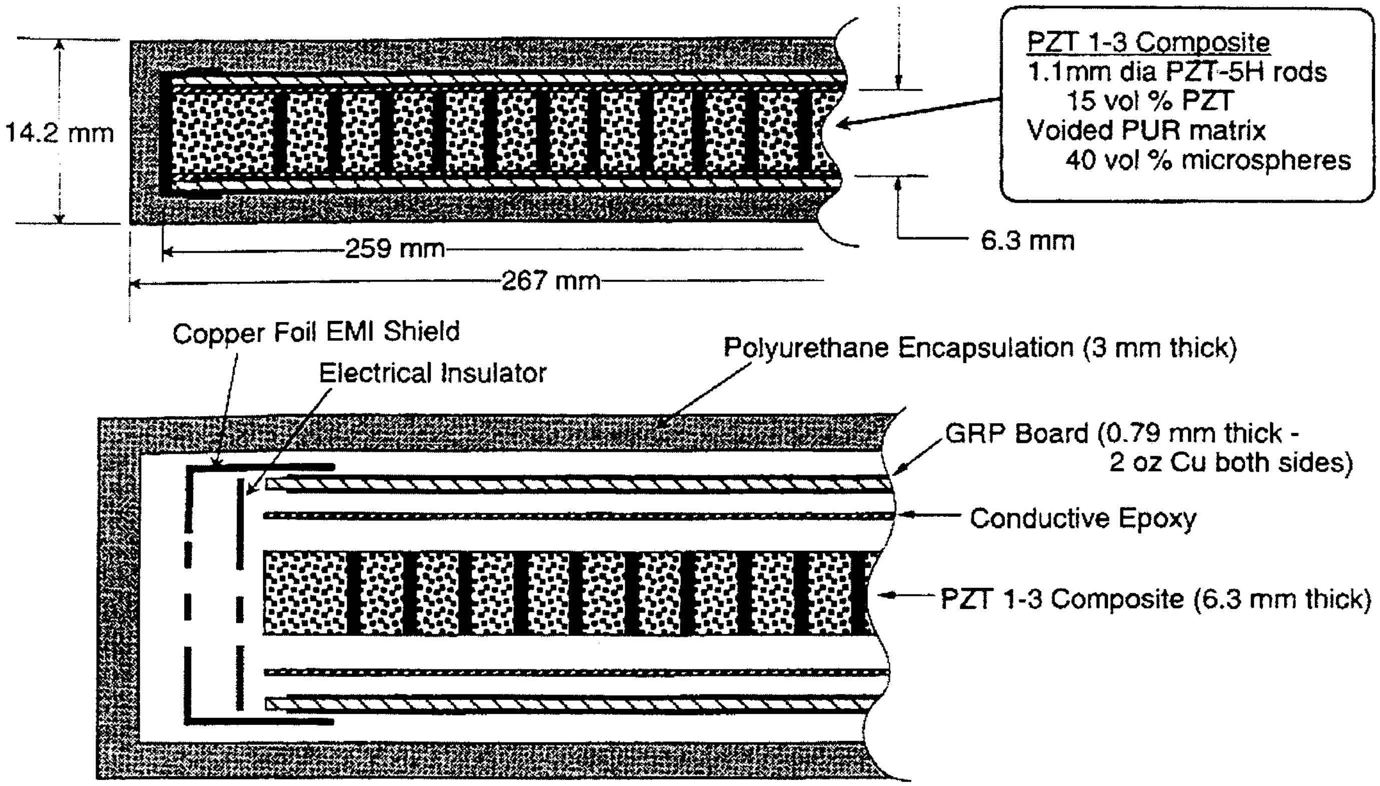

Fig. 2. Cross-sectional view of the SonoPanel™ 1-3 piezocomposite structure [6].

which is adequate for the preparation of small samples such as required in ultrasonic medical imaging applications [5]. However, this method is too costly to meet the need of large area coverage desired in Navy applications, and it is difficult for maintaining material uniformity in large sheets. To meet the Navy application interests, the Office of Naval Research has supported a number of initiatives to explore alternative, low-cost fabrication techniques for the manufacturing of large sheets of 1-3 piezocomposite materials.

One approach is that of MSI in which an injection molding process [6] is used to manufacture 1-3 piezoceramic composites. The initial piezoceramic of choice was Navy Type VI (PZT-5H) piezoceramic powder composition, although MSI has since produced configurations with Navy Type I (PZT-4). Once properly characterized, the piezoceramic powder is thoroughly mixed with a binder to form a viscous slurry. During the injection molding process, the slurry mixture is forced into a cooled mold to form a net shape green part. This part is subsequently heated in air for the removal of the organic binder. Sintering then takes place at 1250°C for one hour in a lead controlled atmosphere to optimize the PZT piezoelectric properties. The preform is then contact poled under a high electric field. Individual preform parts are assembled to the size of a desirable transducer panel and encapsulated by using castable resins such as polyurethane or epoxy under applied pressure. The panel assembly is subsequently cured in a vacuum oven, cooled, and finished before permanent electrodes are applied and wires attached. The final base configuration is a 50 x 50 mm^2 preform, containing a 19 x 19 array of 361 rods. Each rod is 1.1 mm in diameter and about 6.5 mm in height.

Because the original Navy need was for large area hydrophones, MSI initially fabricated the material to address this application. Using published analytical design principles in which the g_h was found to be maximized at the 15% piezoceramic volume fraction [7] with rod aspect ratios on the order of 5 [4], MSI concentrated their early efforts with these material design parameters. The hydrophone intention also implied that the preferred host matrix material should be a soft and lossy polyurethane with a stiff cover plate. The soft and lossy matrix was ensured by placing a 40% volume of 50-μm diameter hollow polymer microspheres into the polyurethane, thus reducing the lateral coupling within the composite structure. Fig. 2 shows a schematic side drawing of the SonoPanel™1-3 piezocomposite material configuration.

The purpose of the cover plates is to average out and stress amplify the incident sound pressure upon the individual piezoceramic rods as well as to provide an electrically solderable connection point. The cover plates are attached by bonding 0.79-mm thick copper clad glass reinforced polymer board (GRP) with a 0.08-mm thick layer of conductive epoxy.

With the interest in hydrophone applications, there also was a concern that the electromagnetic interference (EMI) between neighboring sensors had the potential of being a noise floor problem and thus limiting the signal-to-noise ratio of the hydrophone. To address this, the individual

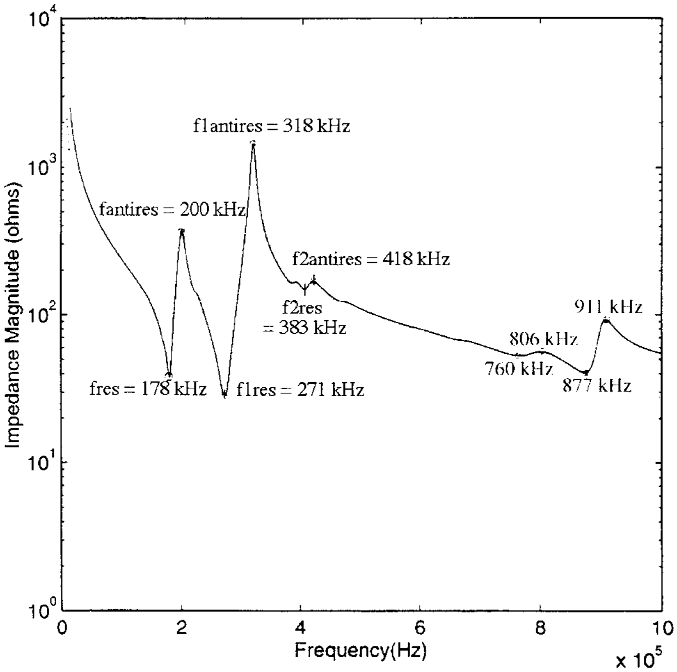

Fig. 3. In-air impedance magnitude of a SonoPanel^{TM} with dimensions 10.16 cm by 10.16 cm by 6.35 mm.

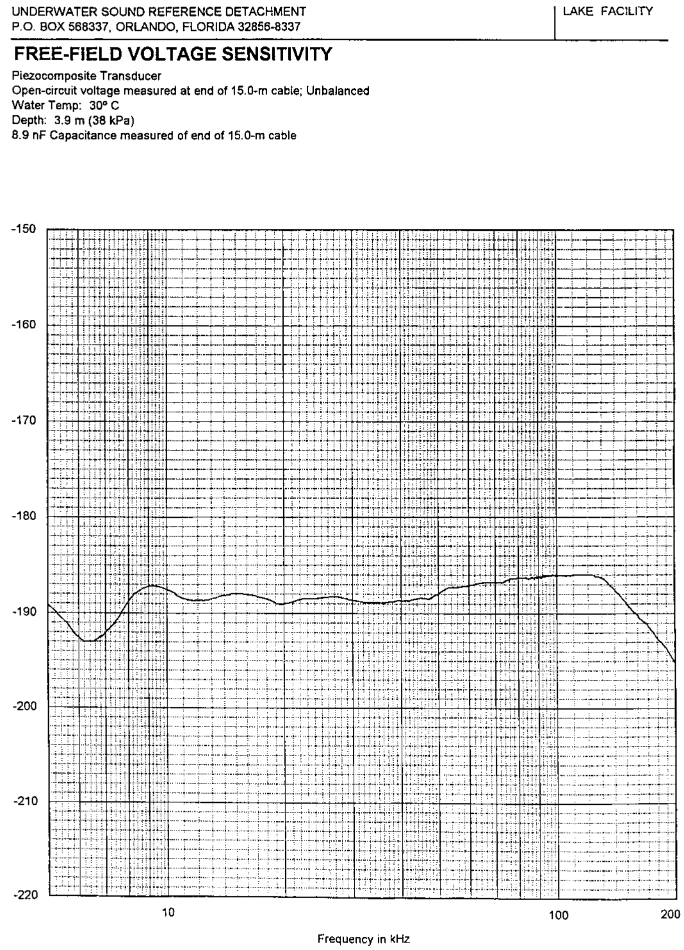

Fig. 4. Measured FFVS of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanel^{TM} in an open water Lake Facility.

panels were shielded by placing a copper foil tape over the edges with an insulating layer placed inside the foil. The shielding foil is soldered to the outer copper sheets along the interfacing edge to form a completely grounded enclosure for the panels.

A 15% piezoceramic volume fraction, Navy Type VI piezoceramic rods based 1-3 piezocomposite SonoPanel^{TM}, has a nominal dielectric constant of 3200 and a density of 1.8 g/cm^3 in which the dielectric constant is simply the volume percentage of the piezoceramic component.

III. In-Air Evaluations

A candidate 15% piezoceramic volume fraction, PZT-5H sample was evaluated in-air for its effective material properties. The sample was 10.16 cm by 10.16 cm by 6.35 mm thick with a spacing of 2.58 mm between each of the cylindrical rods in both the -1 and -2 directions. The measured 1 kHz free capacitance was 8.84 nF with a 0.023 dissipation factor ($\tan\delta$), from which was derived an effective composite free relative dielectric constant (K_{33}^T) of 614.

A measurement of the normal displacement of the radiating surface using laser Doppler vibrometry (LDV) was done at the Naval Research Laboratory in Washington, DC, as a function of frequency for a 1 V drive. This measurement was used to determine an effective longitudinal piezoelectric charge constant (d_{33}) of 562 pm/V, which is within expectations of current Navy Type VI (PZT-5H) material properties.

The effective longitudinal and shear velocities were determined at the former Naval Research Laboratory's Underwater Sound Reference Detachment (USRD) in Orlando, FL. An effective longitudinal velocity of 2260 m/s was determined by placing transducers on both surfaces of the SonoPanel^{TM} sample and measuring the time of flight between the transducers. The shear velocity of the voided polyurethane matrix material (ν_s^p) was determined on a representative matrix material sample as 700 m/s.

Fig. 3 shows the impedance measurement over the frequency range of 100 Hz to 1 MHz. In addition to the expected thickness mode resonance at 178 kHz and the antiresonance frequency at 200 kHz, several other modes are present. Investigations of these modes has found that they generally are related to lateral behavior through the following:

$$f_1 = \nu_s^p/d \tag{2}$$

and

$$f_2 = \sqrt{2} * \nu_s^p/d \tag{3}$$

where d is the spacing between piezoceramic rods, f_1 is the first lateral mode in which the piezoceramic rods and the host matrix vibrate in anti-phase along any diagonal and in-phase along the -1 and -2 directions, and f_2 is the second lateral mode in which the piezoceramic rods and the host

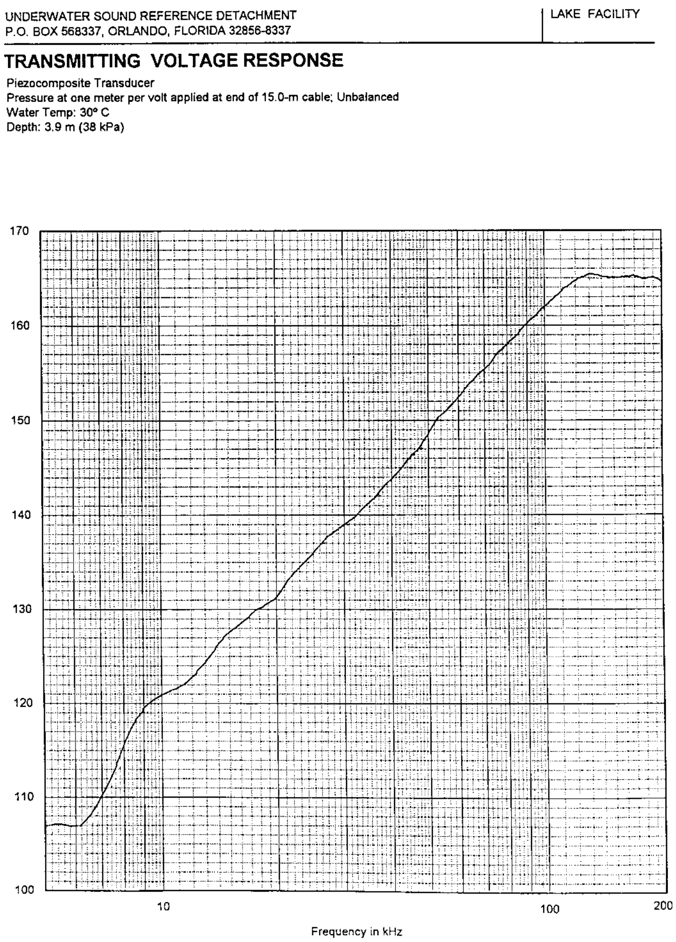

Fig. 5. Measured TVR of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanel™ in an open water Lake Facility.

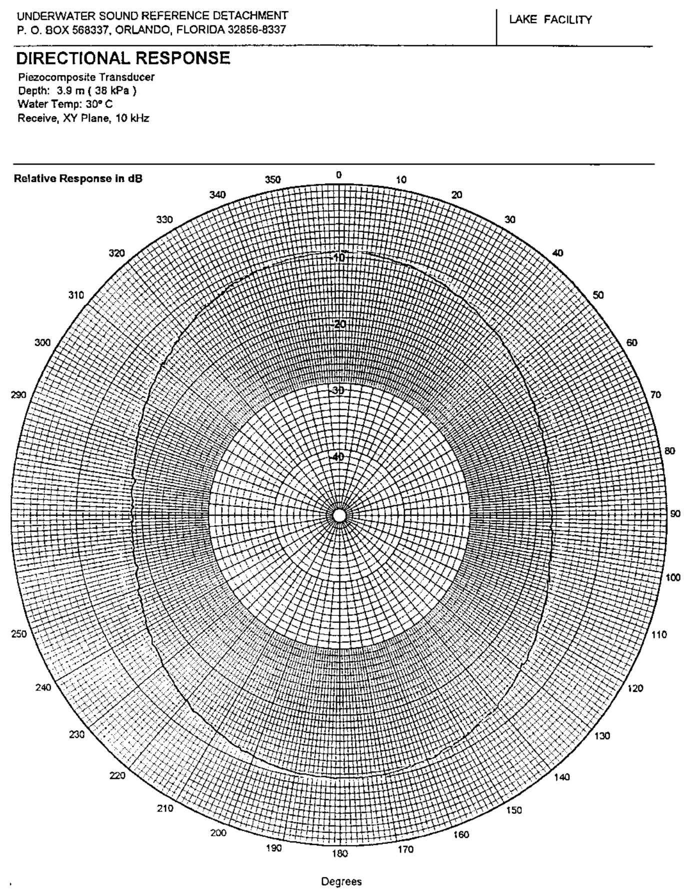

Fig. 6. Measured 10 kHz directivity response of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanel™ in an open water Lake Facility.

matrix vibrate in-phase along any diagonal and in antiphase along the -1 and -2 directions (D. Powell, personal communication and unpublished model, April 9, 1996). However, note that these expressions are approximations and do not account for the influence of the cover plates but provide a general guideline of the expected modal behavior.

The upper frequency modal behavior is related to the dimensional geometry and material constituents of the individual piezoceramic rod in which Fig. 3 shows the radial resonance frequency at 877 kHz and the antiresonance frequency at 911 kHz.

IV. Open Water Acoustic Performance Measurements

Underwater free-field acoustical performance measurements of the 1-3 piezocomposite SonoPanel™ material configurations were performed at the USRD Lake Gem Mary Facility in Orlando, FL. These measurements consisted of free-field voltage sensitivity (FFVS), transmitting voltage response (TVR), acoustic directivity responses, and power linearity as a function of drive voltage. The frequency coverage of the measurements was from 100 Hz to 200 kHz.

The first SonoPanel™ geometry investigated was an active 10.16-cm by 10.16-cm by 6.35-mm sample that was encapsulated in polyurethane for water protection. Fig. 4 shows the free-field voltage sensitivity in units of decibels (dB) referenced to 1 V per micropascal at the face of the sample. The response was not corrected for the electrical load due to the cable capacitance which means that the sensitivity response should be increased by an additional decibel. A low frequency mode below 10 kHz is believed to be related to flexure within the cover plates. The remainder of the response is fairly constant throughout the frequency band until 130 kHz, when the response begins to roll off. This lower frequency resonance frequency roll off (as compared to the observed in-air thickness resonance frequency of 178 kHz) may be partially attributed to the additional mass loading onto the sample from the polyurethane encapsulant.

The transmitting voltage response (TVR) of the SonoPanel™ sample is shown in Fig. 5. The TVR is reported in decibels referenced to one micropascal per volt at 1 meter. In addition to the thickness mode near 130 kHz, both plots also show the presence of additional modes between 130 kHz and 200 kHz, the origins of which are believed to be related to the spacing between the piezoceramic rods. The increase in TVR with frequency is slightly

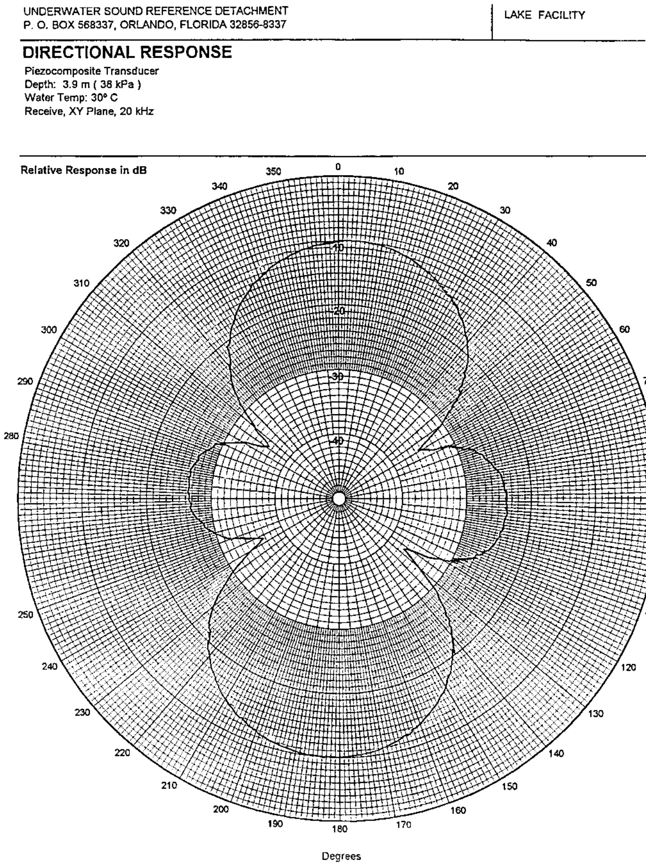

Fig. 7. Measured 20 kHz directivity response of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanel^{TM} in an open water Lake Facility.

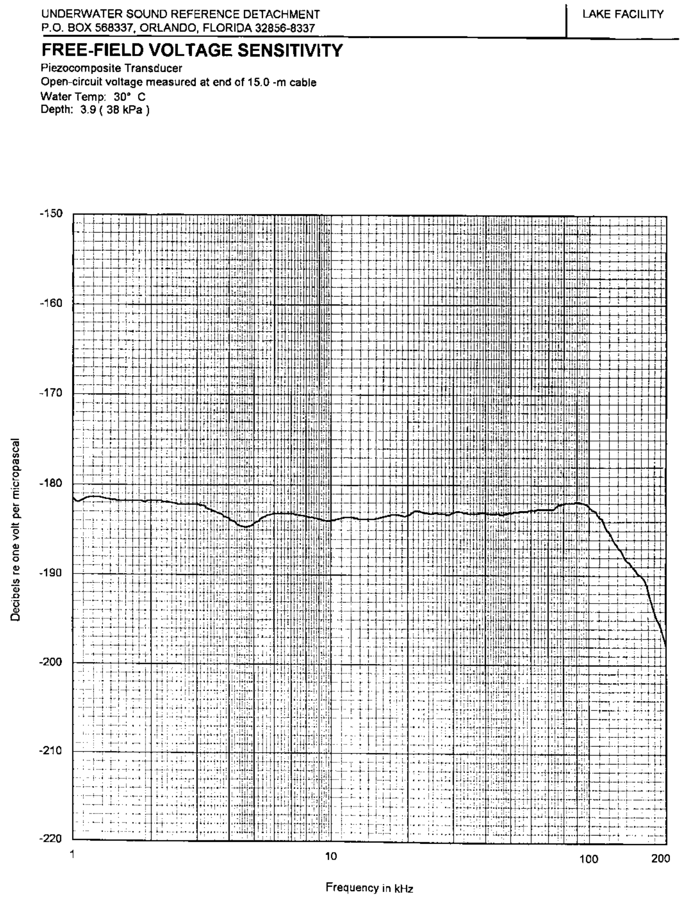

Fig. 8. Measured FFVS of a 25.4 cm by 25.4 cm by 6.35 mm SonoPanel^{TM} in an open water Lake Facility.

greater than the normal 12 dB per octave change, indicative of the overall panel displacement being different from that expected of an idealized point source. The main reason for this difference is the presence of the parasitic modes observed in-air; however, the behavior between 130 and 200 kHz appears to result in a response with improved acoustic bandwidth. An attractive feature of the TVR is the general lack of other modes in the frequency range of 10 to 130 kHz that would normally be noted in a transmit response due to the dimensional features of a transmitting panel.

Fig. 6 and 7 show the acoustic directivity responses of the same sample at 10 and 20 kHz, respectively. The responses are well behaved and indicative of a pure piston mode transduction mechanism of the same dimensions.

A 25.4-cm by 25.4-cm by 6.35-mm thick SonoPanel^{TM} geometry was similarly water protected with a polyurethane encapsulation, then investigated for its acoustic performance in the Lake Gem Mary Facility. Fig. 8 shows the FFVS for this sample. It appears in good agreement with the response of the smaller sample response shown in Fig. 4, including similar modal behaviors and sensitivity levels with the exception of the thickness resonance frequency observed to occur at 100 kHz; this is down from the 130 kHz observed in Fig. 4. The TVR of this sample is presented in Fig. 9, and the same modal behavior responses seen for the smaller sample of Fig. 5 are noted, with the exception of the upper frequency modal behavior.

The success of the low modal contamination in the transmitting responses, coupled with the clean piston mode directivity responses has resulted in increased interest for using these panels in underwater transmitting applications. To study the acoustic output linearity as a function of drive voltage, the 25.4-cm by 25.4-cm by 6.35-mm thick SonoPanel^{TM} sample was driven at 100 V_{rms}, 200 V_{rms}, 500 V_{rms}, 700 V_{rms} and 900 V_{rms}. The results of this study are presented in Fig. 10 in which the sound pressure level is shown to increase linearly as a function of the drive level. The study was concluded at 900 V_{rms} because of amplifier limitations.

V. Acoustic Performance Under Hydrostatic Pressure

Underwater acoustical performance evaluations of the 1-3 piezocomposite SonoPanel^{TM} material configuration were investigated as functions of hydrostatic pressure and temperature. These measurements were done at the USRD high pressure Anechoic Tank Facility (ATF). The frequency coverage of the measurements was from 10 to

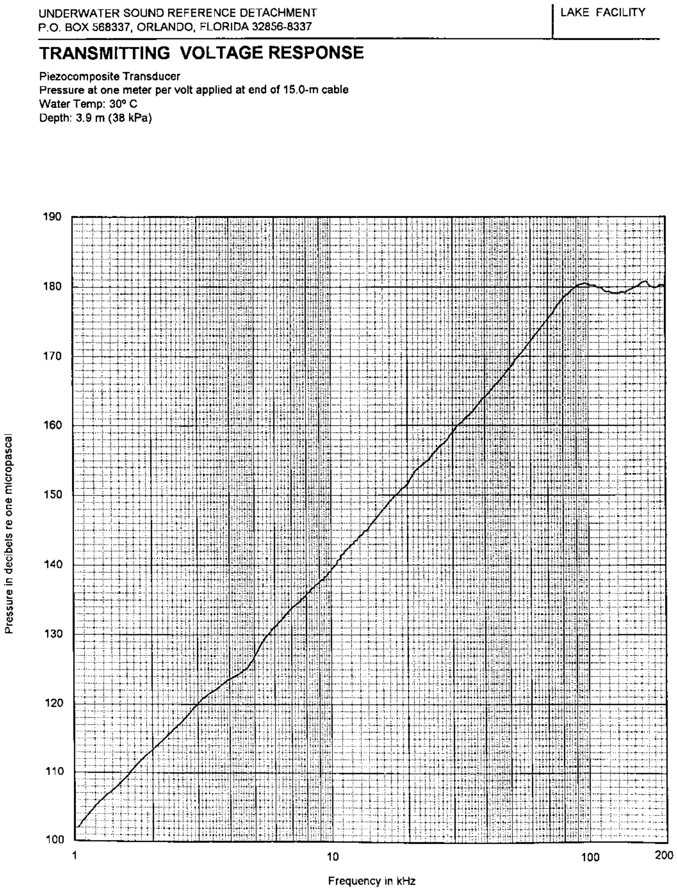

Fig. 9. Measured TVR of a 25.4 cm by 25.4 cm by 6.35 mm SonoPanel™ in an open water Lake Facility.

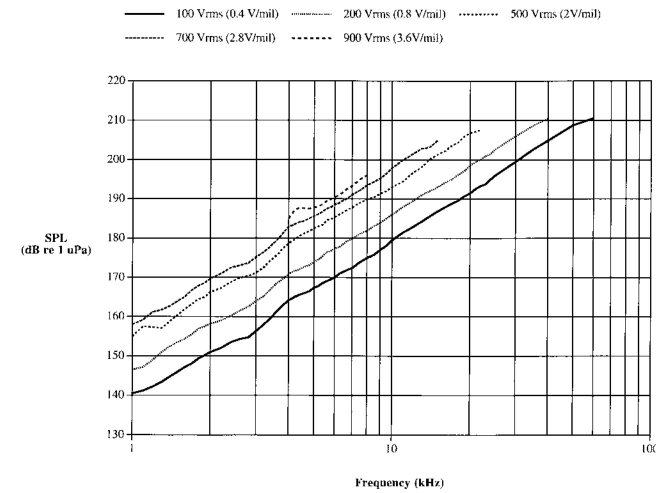

Fig. 10. Measured SPL of a 25.4 cm by 25.4 cm by 6.35 mm SonoPanel™ in an open water Lake Facility for drive voltages of 100 V_{rms}, 200 V_{rms}, 500 V_{rms}, 700 V_{rms}, and 900 V_{rms}.

100 kHz at the discrete temperatures of 4 and 22°C under hydrostatic pressure conditions ranging from 138 kPa to almost 7 MPa. The sample used for these measurements was the same 10.16-cm by 10.16-cm by 6.35-mm sample initially evaluated in the Lake Gem Mary Facility.

The effect of the hydrostatic pressure cycling and low temperature exposure on the TVR is demonstrated in Fig. 11. When measured at 4°C, the TVR showed a few decibel variations due to the change in pressure when stepping up from 3.5 to 6.9 MPa, then reduced to 3.5 MPa before returning the system to the ambient pressure. This suggests that the extreme high pressure of 6.9 MPa had a slight effect in degrading the transmitting response, but the response quickly adapted to the new hydrostatic pressure exposure. No changes were noted in the responses as a function of hydrostatic pressure at 22°C.

The low temperature and hydrostatic pressure effect on the overall acoustical property of the SonoPanel™ sample is perhaps more clearly seen when examining the FFVS response of Fig. 12. Nominally a constant FFVS at −185 to −186 dB was observed over the frequency band of the measurement. When pressure cycling was carried out at 22°C, with the pressure varied between ambient pressure to a maximum of 6.9 MPa, the effect on the acoustic performance was found to be less than 1 dB degradation. After the release of this pressure, the material appeared to recover fully with no change from the original FFVS characteristics. When tested at 4°C, the sensitivity decreased by as much as 4 dB, which suggests that the host matrix polymer properties need to be stabilized before full performance may be realized. The sample returned to its initial performance upon release of the pressure.

VI. Underwater Explosive Shock Tests

In many underwater applications, there is an interest in assuring that an underwater system can withstand an underwater explosive shock and continue to be operationally effective after this exposure. In order to quantify the criteria of the shock, a set of criteria has been established [8]. Fulfillment of this specification requires the structure being examined to remain functionally operational after a series of explosions at four ranges: shot 1 is directed to the edge of the test structure at a distance between the explosion and the test structure of 12 meters, shots 2 through 4 are oriented for broadside interaction at distances of 9, 7.6, and 6 meters, respectively. The explosive charge weight and composition is 60 lb of HBX-1 at a test depth of 3 meters.

Fig. 13 (top) shows a pressure signature from a 9 meter range open-water test shot at the former Hunters Point Navy test facility in California [8]. The peak pressure here is equivalent to approximately 14 MPa with the recoil from the floating platform occurring 600 msec after the peak pressure. The profile for the 6 meter broadside explosion is similarly shaped with a peak pressure of 18 MPa.

The USRD developed a facility to expedite this process for small transducer samples. This facility is the Conical Shock Tube (CST) Facility, which duplicates the conditions of the open-water shock tests, but with a size limitation that the test object fit inside a 10-inch diameter cylinder [9]. The concept of the CST is that, when an explosive charge such as 27.2 kg of HBX-1 is detonated in the

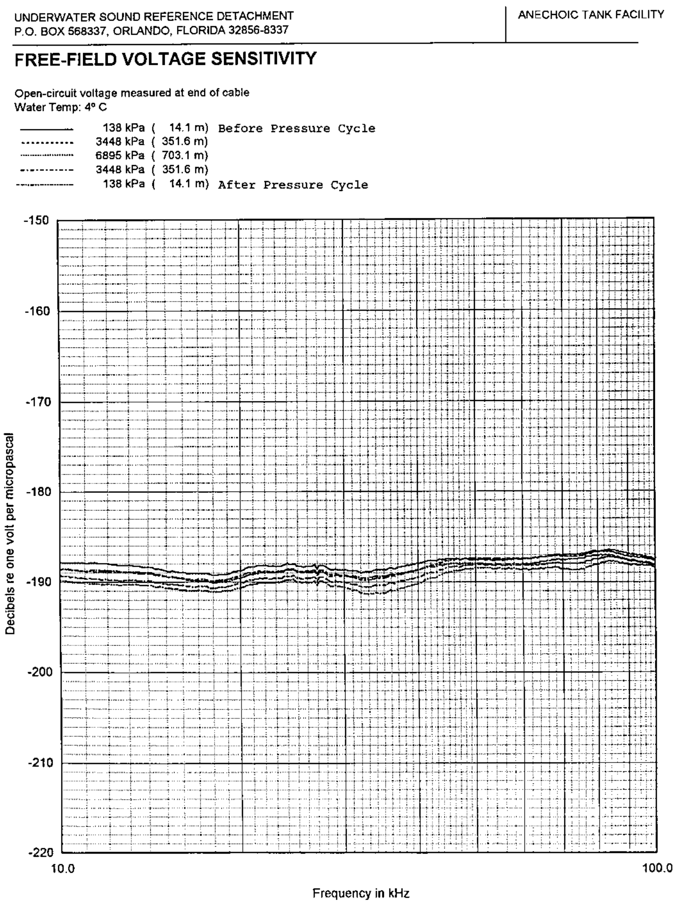

Fig. 11. Measured TVR of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanel^{TM} as a function of hydrostatic pressure and at 4°C in an anechoic tank facility.

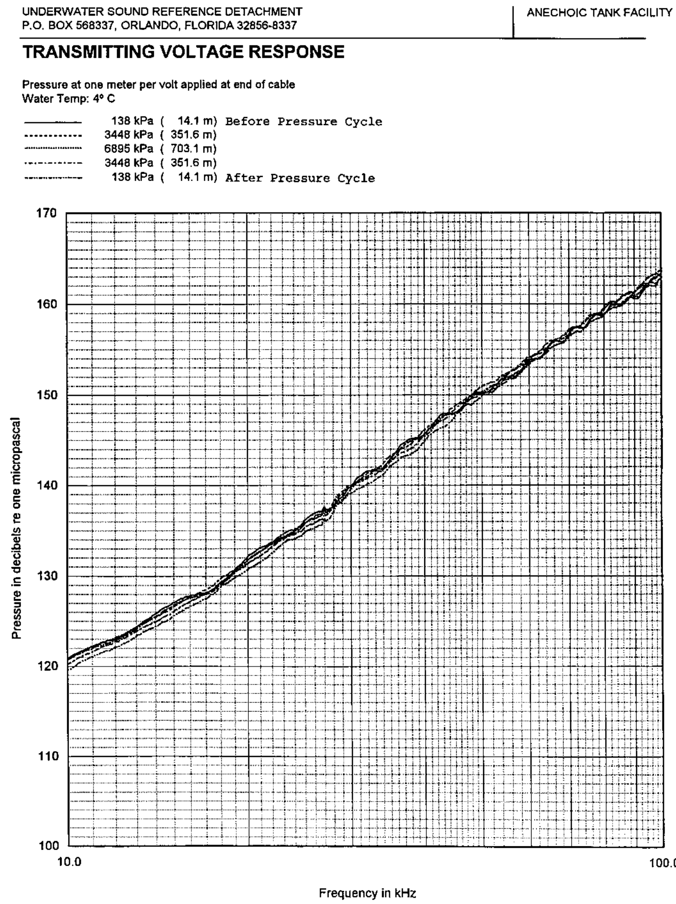

Fig. 12. Measured FFVS of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanel^{TM} as a function of hydrostatic pressure and at 4°C in an anechoic tank facility.

open water, a spherical shock pressure wave is propagated out from the explosion in all directions. The conical bore of the CST represents a small angular sector of the sphere such that an explosive shock pressure wave of the same intensity can be produced by a small angular sector of the original charge at the vertex of the cone. This also means that, by using a charge weight of a #8 blasting cap and less than 1 gram of flexible booster explosive, a shock wave can be produced that is equivalent in peak pressure and time profile to that of the 6 meter range broadside impact. To try and maintain the exact profile of the open-water shock tests, a sliding piston was installed in the CST behind the location of the test device. This piston behaves in a similar recoil fashion as that of the actual floating platform.

To investigate whether functional performance changes occur in the 1-3 piezocomposite plates after exposure to underwater shock in the CST, acoustic measurements were conducted at USRD in the Lake Gem Mary Facility for the 1 k to 200 kHz frequency range and in the High Frequency Calibration Facility for the 200 k to 400 kHz frequency range. Acoustic measurements included the TVR, FFVS, and directivity responses.

After initial acoustic measurements, the SonoPanel^{TM} sample was exposed to shock waves representative of a broadside 6 meter range explosive shock in the CST Facility. Fig. 13 (bottom) shows the shock pressure signature for this explosion. When compared with the shock wave pressure profile of Fig. 13 (top), the CST shock wave peak appears more rounded. Also, higher frequency overtones produced noticeably more scatter in the pressure response as a function of time. Both of these characteristics are traits of the steel tube. Although the appearance on the pressure wave profile is different, this high frequency energy does not contribute much to the total energy in the spectrum [9]. A conversion of the units in Fig. 13 shows good agreement between the two pressure profiles in terms of time scale occurrences. The pressure levels for Fig. 13 (top) are less because its profile is for a 9 meter range and that of Fig. 13 (bottom) represents a 6 meter range.

Fig. 14 is a presentation of the TVR [Fig. 14 (a)] and FFVS [Fig. 14 (b)] for a SonoPanel^{TM} 1-3 piezocomposite sample before and after the underwater explosive shock exposure. In fact, because there was no degradation after the first explosive shock exposure, this transducer was later exposed a second time and acoustically measured a third time. Again, no degradation was observed in the transmitting and receiving responses. Note that the slight differences seen above 180 kHz are due to mounting errors during the acoustic measurements and are not a resulting indication of the shock exposure.

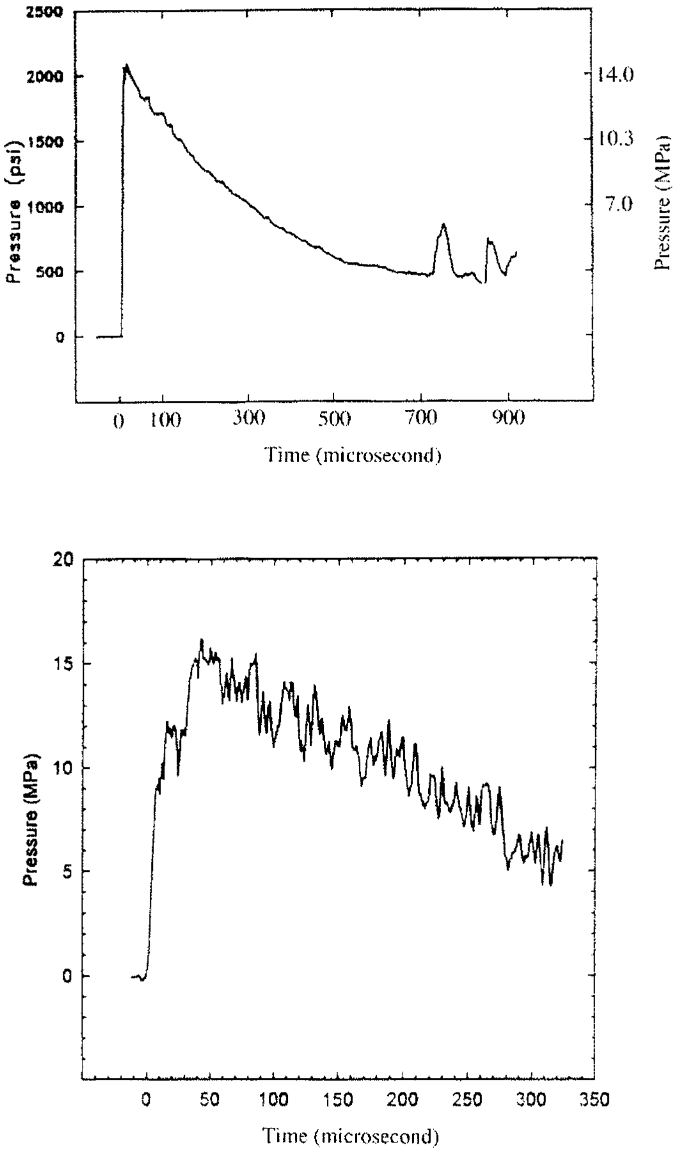

Fig. 13. Top. Open-water shock pressure wave profile from a 9 meter range broadside test shot at the former Hunters Point Shock Facility. Bottom. Conical shock tube pressure wave profile for an equivalent broadside 6 meter range test shot. This profile was recorded during the exposure of the SonoPanel^{TM} sample.

VII. Summary

A specific 1-3 piezocomposite configuration known as the SonoPanel^{TM} has been fabricated by using a cost-effective injection molding technique. The in-air and in-water measured performances show not only modal behaviors related to piezoceramic rod spacings and matrix polymer selections, but they also show a relatively well behaved acoustic response. The measured underwater directivity responses suggest a pure piston mode response. The present panel configuration appeared to be stable with hydrostatic pressure up to 6.9 MPa and is resistant to explosive shock as determined from tests in a conical shock tube. The underwater acoustical performance suffers its most severe test when the composite panel is exposed to

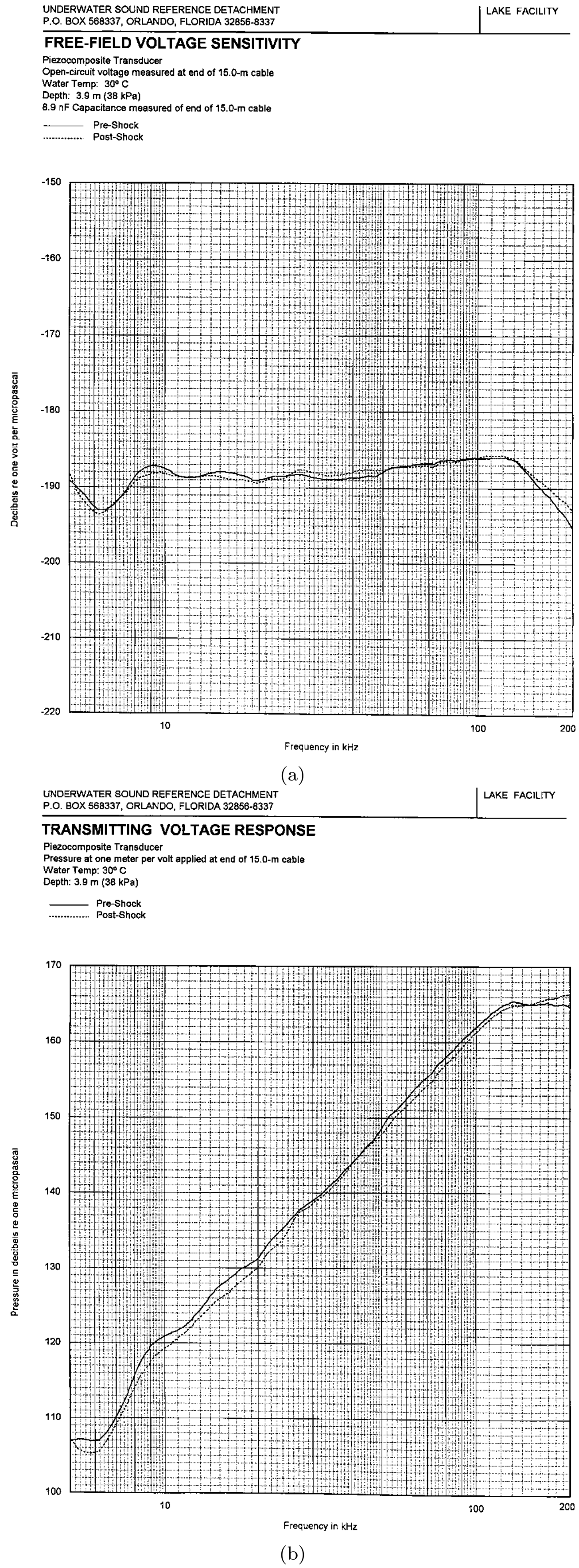

Fig. 14. Measured TVR (a) and FFVS (b) for the SonoPanel^{TM} 1-3 piezocomposite structure before and after the underwater explosive shock exposures.

the combination of high hydrostatic pressure of 6.9 MPa and a low temperature of 4°C. In summary, the 1-3 piezocomposite SonoPanel^{TM} configuration has high sensitivity, flat broadband response, and linearity with respect to drive voltage. This material configuration appears to be a promising candidate for underwater transducer applications when large area coverage is desired.

Acknowledgements

The authors wish to thank Drs. L. J. Bowen and R. L. Gentilman of Material Systems, Inc., for their support in piezocomposite panel fabrication. Dr. David Powell of Weidlinger Associates is acknowledged for his contributions in determining the in-air modal behavior of the piezocomposite samples. The authors also with to thank the reviewers for their careful and insightful comments.

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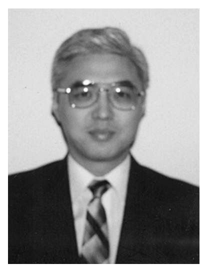
Thomas R. Howarth (M'96) was born in Philadelphia, PA, and received the following degrees from The Pennsylvania State University: B.S. in electrical engineering (1982), M.S. in engineering science (1988), and Ph.D. in engineering science and mechanics (1991) with further graduate study at the University of Rhode Island in the Department of Ocean Engineering (1982–1987).

Since 1995 he has been a Staff Research Engineer of the Physical Acoustics Branch in the Acoustics Division at the Naval Research Laboratory in Washington, DC. He is involved in the R&D of acoustic transduction technologies with an emphasis on implementing recent laboratory materials developments into prototype and conceptual devices. Previous positions include the Naval Research Laboratory's Underwater Sound Reference Division in Orlando, Florida (1991–1995); The Pennsylvania State University (1988–1991); and the Submarine Signal Division of Raytheon Company in Portsmouth, Rhode Island (1981–1988). He is a Fellow of the Acoustical Society of America and the current Chair of the Engineering Acoustics Technical Committee (1997–2000).

Dr. Howarth holds two patents (with another four pending), presented and/or published more than 70 papers, and was the charter recipient of the ASA Structural Acoustics TC's First Prize in the Student Paper Competition in May 1991. He is a member of Tau Beta Pi.



Robert Y. Ting was born in China and received his B.S. from the National Taiwan University in 1964. He received graduate training at MIT (M.S., 1967) and the University of California at San Diego (Ph.D., 1971).

Dr. Ting began his Naval Research Laboratory (NRL) career in 1971 in Washington, DC, working in the areas of polymer drag reduction, polymer rheology, composite materials, and adhesion science. In 1980 he was promoted to be in charge of the Navy's basic and applied research in underwater acoustical materials at NRL's Underwater Sound Reference Division in Orlando, FL. In addition to polymeric materials, his group was involved in the research of a wide range of new piezoelectric materials for the Navy's sonar transducer applications. Dr. Ting retired from the U. S. Navy in 1997. He now is Professor of Chemistry and Materials Engineering at the University of Central Florida in Orlando. He has published extensively and is a Fellow of the Acoustical Society of America.