Acoustic projectors for AUV and UUV applications in shallow water regions

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ABSTRACT

For acoustic identification of objects in a littoral environment, there are generally three frequency bands of interest; 1 kHz to 10 kHz, 10 kHz to 100 kHz and 100 kHz to ≥ 1 MHz, where the selection of these bands is dependent upon the specific Navy mission. This paper will discuss the progress of the Naval Research Laboratory in developing acoustic projector prototypes to address the lower two frequency bands for unmanned underwater vehicle (UUV) and/or autonomous underwater vehicle (AUV) applications. The band of 1 kHz to 10 kHz is currently being addressed using cymbal flextensional vibrator elements sandwiched into thin panels. In-air data has shown that high levels of acoustic displacement at low frequencies are possible with these devices while more recent in-water data has verified these expectations. This success has led to modelling and prototyping of similar devices for shallow water regions. The frequency range of 10 kHz to 100 kHz has been investigated for several years where the acoustic projector was originally reported during AeroSense 1998. The results of integrating the NRL broadband projector into the NSWC/Coastal Systems Station (CSS) synthetic aperture sonar (SAS) UUV will be presented. This system integration considers the projector as a constant source level over the 10 kHz to 100 kHz band by driving the 100 kHz resonant transducer with an inversely shaped transformer. The presentation will conclude with a discussion of the future development trends in shallow water transducers for AUV and UUV missions.

Keywords: piezocomposite, broadband, cymbals, transducer, projector

INTRODUCTION

The Naval Research Laboratory (NRL) has been involved in the development of advanced identification algorithms as functions of frequencies and bandwidths. Low frequency methods are currently being pursued to identify objects based upon their structural acoustic signatures[1] while broadband middle frequency techniques are being investigated to form acoustic daylight detection and identification techniques[2, 3]. However, to implement these new detection and identification techniques on autonomous underwater vehicle (AUV) and/or unmanned underwater vehicle (UUV) platforms, it is necessary to develop advanced acoustic transduction hardware. This paper presents an overview of current research and development of acoustic projectors to address the lower two frequency bands for these mobile platforms in shallow water regions.

1. WIDE BAND PROJECTOR

For the purposes of this paper, we are classifying the middle frequencies as those in the frequency range of 10 kHz to 100 kHz. Most current AUV or UUV applications feature either tonpilz (piston) transducers or resonant piezoceramic bars in this band. Although both of these technologies provide high acoustic output at a specific frequency, these technologies are limited in terms of operating bandwidth and it is the extended bandwidth that is desired for the advanced algorithms[2, 3].

These transducers are typically used because of cost savings in terms of transducer developments but they also compromise the system performance potential in terms of operating frequency, operating bandwidths and volume occupation within a vehicle. During the last five years, the Naval Research Laboratory (NRL) has been investigating the use of 1-3

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piezocomposites for application on AUVs and UUVs. In 1995, a suitable 1-3 piezocomposite material configuration design was selected such that in 1996, NRL was able to develop a multilayered, broadband 1-3 piezocomposite to replace a 20 kHz projector in the CSS low frequency synthetic aperture SONAR (LFSAS) program[3, 4, 5].

In 1998, NRL participated with Northrop Grumman's Oceanic Division (NG/Oceanic) in Annapolis, MD investigating the system efficacy of using the 1-3 piezocomposite based broadband projector for the CSS UUV mounted SAS system. The specific study was to examine whether the NRL transducer could deliver the necessary acoustic output in a linear fashion over the frequency band of 10 kHz to 100 kHz. To investigate this goal, NRL provided NG/Oceanic with the NRL produced LFSAS broadband projector and then participated with electroacoustic testing at NG/Oceanic.

1.1. Transducer Operating Limits: Thermal Calibration

A concern for driving the NRL LFSAS projector has been whether the transducer would remain linear as the temperature was increased. Generally the electrical capacitance of a piezoelectric ceramic will rise with increasing temperature. This has also been assumed to be true of piezocomposite materials such as the 1-3 piezocomposite used in the NRL LFSAS projector. However, this effect had never before been investigated. To study this, the transducer with cable was placed into an oven along with a thermometer. The temperature was raised in steps where each step was long enough to reach the steady state of the piezocomposite at that temperature. Figure 1 shows the measured results of capacitance (as measured at 1 kHz) versus temperature. The measured points are in a straight line where the first point was measured AFTER the last point, thus providing confidence in the approach. The upper limit of 120 degrees F was chosen in order to guarantee no damage to the polyurethane encapsulant. It is significant in that the time constant was very long in order for the transducer to reach a stable temperature. The reasoning for this long time lag is thought to be the thermal resistance of the polyurethane encapsulant and the Syntech decoupling frame. The implication of this is that if the transducer generates excessive heat, some means of thermal conduction via the electroding and/or backing structure should be considered[6].

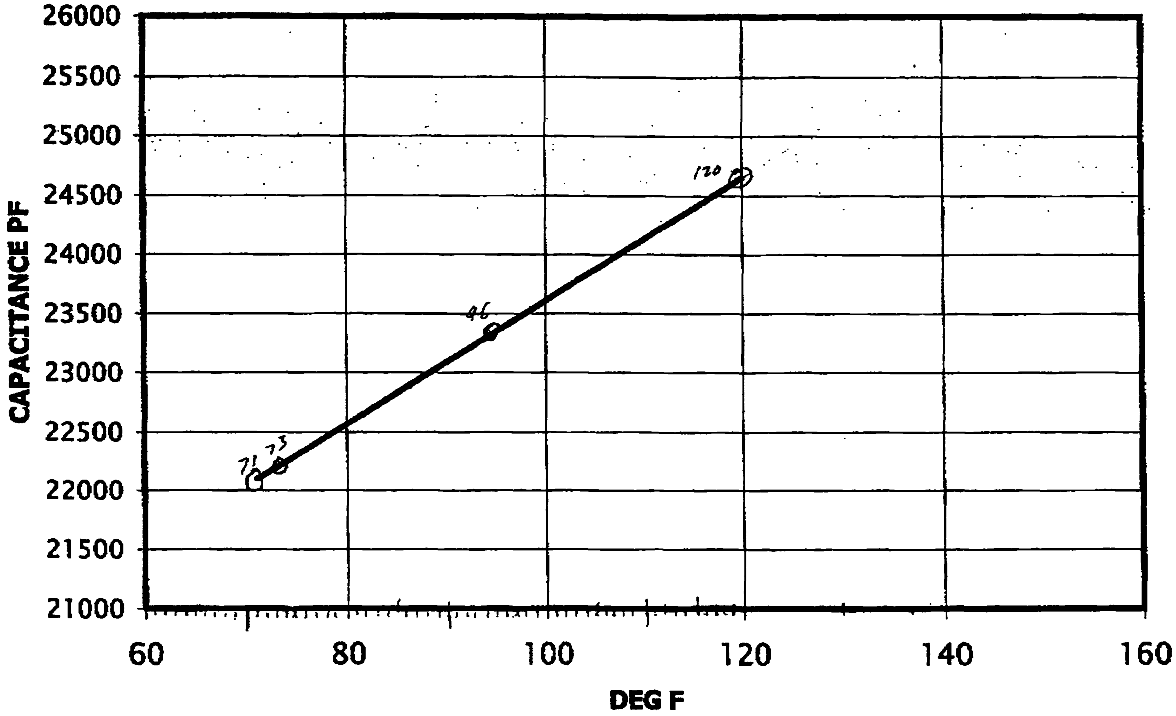


Figure 1: Measured capacitance versus temperature for NRL SAS projector[6].

1.2. Transducer Operating Limits: Determining Safe Conditions

There are typically three different failure mechanisms for piezoelectric ceramic transducers. Recent studies have shown that these same piezoceramic failure mechanisms also apply to 1-3 piezocomposite materials[7, 8, 9]. The three common failure modes are described by the following,

1. Exceeding the electrical stress displacement (i.e., exceeding the voltage or volts/mil) limit of the piezoceramic component. This type of failure commonly results in a depoling (electrical breakdown) of the piezoceramic element. In 1-3 piezocomposite materials this type of failure is difficult to realize because of the host matrix composition where the host matrix will typically fail before the piezoceramic. However this type of failure is common in pure piezoelectric ceramic based transducers.

2. Pure mechanical stress caused by the inertia of the mechanical load when the piezoceramic is in tension. This stress is a maximum at the mechanical resonance frequency of the piezoceramic because this is the frequency where the piezoceramic has its maximum capacitance and thus, lowest electrical impedance. A recent study of 1-3 piezocomposite materials driven with a low duty cycle found that this failure mechanism was induced for Navy Type VI piezoceramic rods with a breakdown of 4 V/mil while Navy Type I piezoceramic rods showed operation past 13 V/mil. Both of these limits exceed traditional piezoceramic limits[7, 8]. The failure mechanisms of the 1-3 piezocomposite materials were graceful and not catastrophic as found with piezoceramics.

3. Temperature build-up, where Navy Type VI piezoceramic is particularly vulnerable because of the high dielectric hysteresis of the ceramic composition. For 1-3 piezocomposite materials the thermal build-up will actually cause the host matrix component to melt first thus resulting in a catastrophic failure of the transducer. This type of failure was recently noted for high drive CW conditions of 1-3 piezocomposite materials[9].

This last failure mechanism can be further examined without inducing the other failure mechanisms described by 1 and 2 if a relatively low voltage is used well below the thickness resonance frequency (which is 100 kHz for the NRL LFSAS transducer). A frequency of 20 kHz with a 143 Vrms (maximum undistorted amplitude of test system) and variable duty cycle were initially used. These results showed that a maximum temperature rise of 1 to 2 degrees F was realized for full CW conditions. To continue the test it was necessary to use an Instruments, Inc. L90 power amplifier for a second test with a 500 Vrms (2 V/mil) drive voltage. Voltage and current were monitored and this drive level resulted in 38.4 VA/in^2 being delivered to the transducer during the tone burst. Current led voltage by essentially 90 degrees. Duty cycles of 10%, 20% and 40% were used as well as a lower voltage (500 x .707) representing half-power. Figure 2 shows the temperatures measured (converted from the capacitance graph of figure 1) for this test. Note that the end and start points essentially coincide. The cluster of four points represent four widely displaced points in time and two energy levels. The 40% duty cycle point represents a measurement taken before steady-state capacitance was reached. Nevertheless, all points lie on a straight line such that the conclusion is that as long as the average volt-amps (VA) is below that represented by the 40% duty cycle point (which corresponds to an average VA of 15 VA/in^2) then operation is safe. This maximum level corresponds to 312.5 Vrms for a CW (100%) duty cycle or 1581 Vrms with a 10% duty cycle[6].

1.3 In-water Transducer Calibration and Linearity

The NRL LFSAS projector was first tested by itself for its low level drive voltage transmit response to compare with previous Navy calibration results. In the Navy tests, the transmitting voltage responses (TVRs) and the 100 V and 500 V drive sound pressure level responses (SPLs) showed a 30 kHz resonance mode as well as the expected 100 kHz thickness resonance frequency. The 30 kHz resonance was partially traced back to a mode between the backing structure and the composite material[4]. However this mode was also thought to have been enhanced from the test rig mounting structure. The rest of the transmitting band was found to increase linearly in the textbook 12 dB/octave manner from 10 kHz to 100 kHz.

In the NG/Oceanic test[10], the transducer was mounted with different rigs such that the mounting system was partially decoupled from the transducer. The measured TVR is shown in figure 3. Note that this response does not show the enhanced 30 kHz mode but demonstrates a linear response over the desired 10 kHz to 100 kHz band. This TVR is representative of the originally expected responses including output levels at 10 kHz of 125 dB re 1 µPa/V @ 1 m which means a 1.8 kV drive is theoretically required to accomplish the strawman SPL goal of 190 dB at 10 kHz. The response also suggests a level of 142 dB re 1 μPa/V @ 1 m at 20 kHz which for a 1 kV drive (4 V/mil) at 20 kHz will theoretically correspond to the goal of a 200 dB SPL. This drive level decreases linearly to 12.5 V drive at 100 kHz to maintain the constant 200 dB SPL[4, 5].

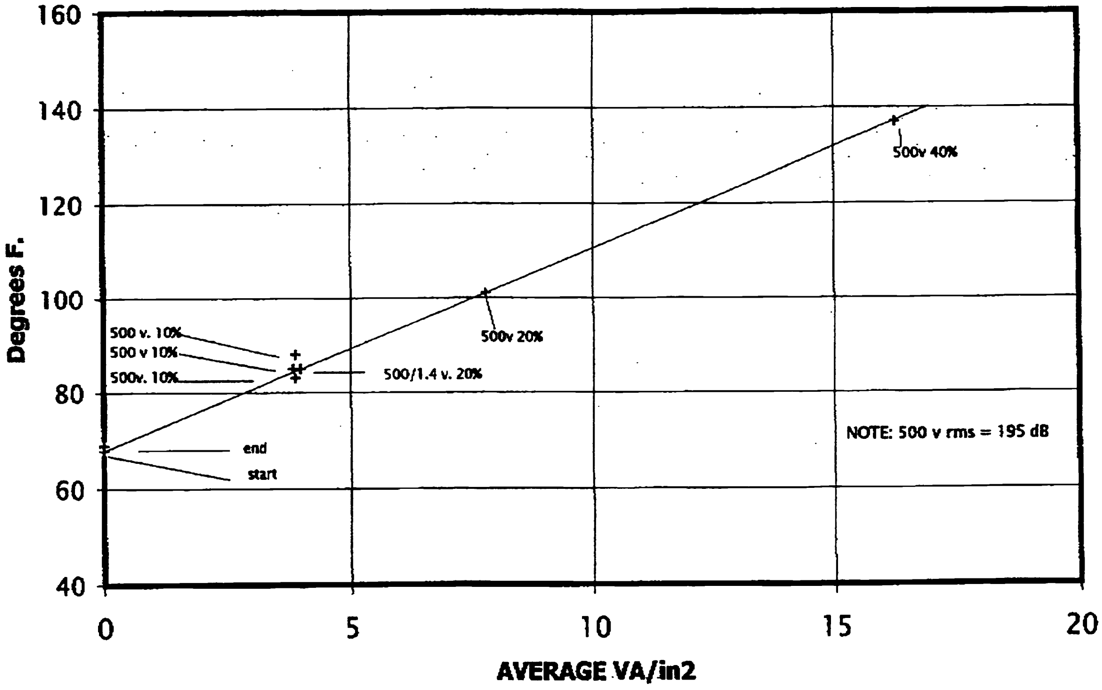


Figure 2: Average volt-amps drive capability versus temperature as measured for the NRL SAS projector[10].

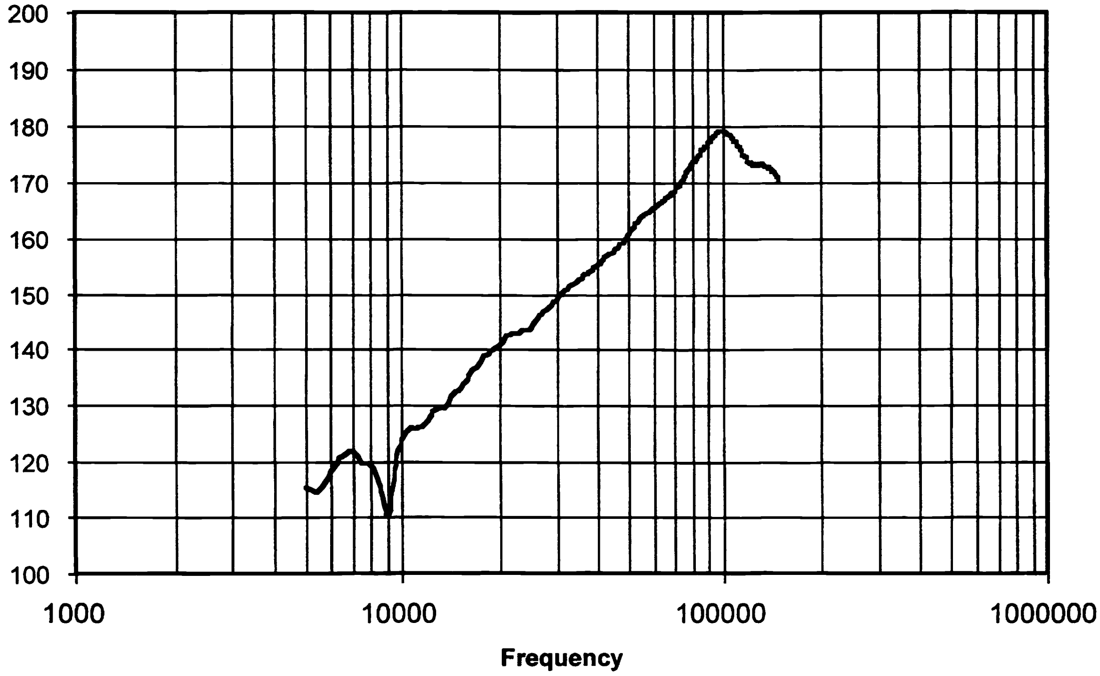


Figure 3: Measured TVR (in units of dB re 1 μPa/V @ 1 m) versus frequency for NRL SAS projector[10].

After the low level calibration response, specific frequencies were selected to examine the high power acoustic output of the transducer. Figure 4 shows the linearity responses for 10 kHz, 20 kHz, 50 kHz and 100 kHz frequencies[10]. The drive voltage was increased in known voltage steps with the projector output signal monitored for waveform (and hence distortion) at each frequency and step. The input drive voltage and current were monitored to verify an absence of harmonics in the drive signal. The drive voltages were increased at each frequency until either 1 kVrms was reached or signs of waveform distortion were noted in the hydrophone output.

The results presented in figure 4 are for the range and maximum SPL achieved without distortion. At 10 kHz, this level was 187.3 dB, at 20 kHz it was 203.6 dB, at 50 kHz it was 209.8 dB while 212 dB was reached at 100 kHz. At the maximum levels for 10 kHz and 20 kHz the hydrophone waveforms began to show signs of distortion.

These results indicate that the strawman goal of 190 dB at 10 kHz is off by 2.7 dB but that all other desired SPLs (greater than 200 dB for 20 kHz and higher) can be accomplished in terms of the *transducer* output capability[10]. After a couple of minutes of high drive operation, the transducer capacitance was rechecked and found to be essentially the same as before the tests. This indicates that the transducer is stable in terms of low duty cycle drive conditions.

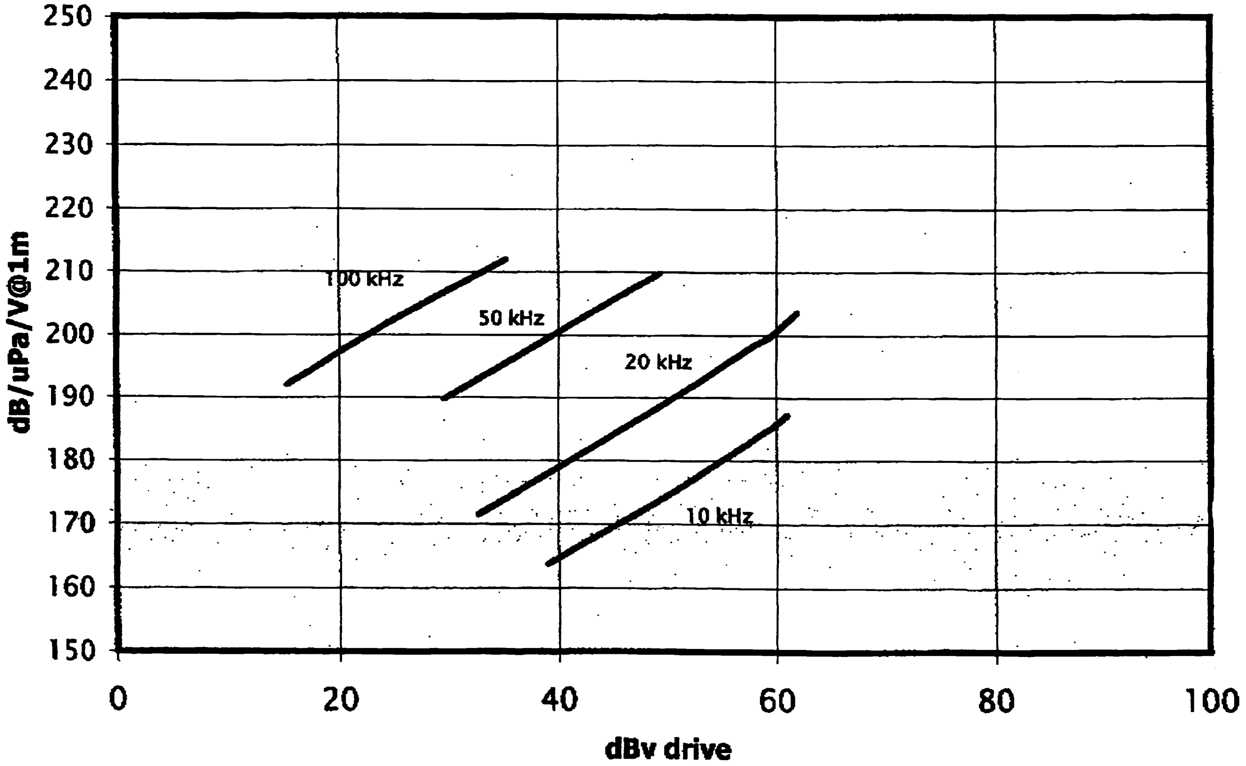


Figure 4: Measured linearity at 10, 20, 50 and 100 kHz in terms of drive level versus acoustic output for NRL SAS projector[10].

The 1998 tests at NG/Oceanic revealed several aspects of the NRL broadband transducer approach. The NRL LFSAS projector appears capable of meeting the original programmatic goals in terms of acoustic performance. In fact the overall response now appears to be more desirable than that of previous calibrations because of the isolation in the transducer mounting arrangement. With the exception of the 2.7 dB acoustic output deficit at 10 kHz, the transducer showed a strong high drive acoustic output response through the remainder of the desired operating decade. The transducer also showed that for the desired LFSAS system duty cycles, it will operate in a safe manner void of typical transduction failure mechanisms.

2. LOW FREQUENCY PROJECTORS

Recently, NRL has been developing thin profile, low frequency acoustic projectors for shallow water applications. These projectors are based upon the cymbal flextensional driver that was originally developed at the Materials Research Laboratory of The Pennsylvania State University under the Office of Naval Research support[11, 12].

2.1 Single Element Cymbal

The cymbal actuator consists of a poled DoD Type VI piezoceramic disk that is placed between and mechanically coupled to two brass caps, each of which contains a shallow air-filled cavity on its inner surface as shown in figure 5. The caps convert and amplify the small radial displacement and vibration velocity of the piezoceramic disk into a much larger axial displacement and vibration velocity normal to the surface of the caps.

The caps are prepared by first cutting blank disks from a sheet of metal foil, in this case 0.20 mm thick brass. These blanks are shaped using a die press to produce the desired dimensions. The caps are then bonded to the poled PZT disk using a very thin (approximately 20 µm) layer of epoxy. Finally, the entire assembly is allowed to cure at room temperature for at least 24 hours while under moderate pressure.

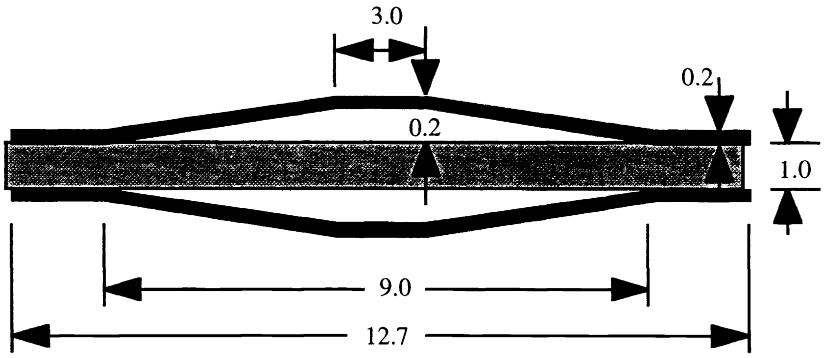


Figure 5: Single cymbal flextensional driver element (dimensions in mm)[13].

2.2 Cymbal Panels

NRL places the individual cymbal elements into an eight by eight parallel arrangement between two stiff cover plates as shown in figure 6. This configuration is intended to produce a larger area piston plate motion with a uniform surface displacement/force profile and a low resonance frequency. The stiff cover plates are carbon fiber reinforced graphite composite plates which are nearly as stiff as stainless steel but are over five times lighter. The cover plates are copper electroplated to form the electrical attachment electrodes for driving each of the elements in parallel since the sixty-four individual elements are each attached to the plates with a silver conducting epoxy. The overall dimensions of the panel are 101.6 mm by 101.6 mm by 6.35 mm thick.

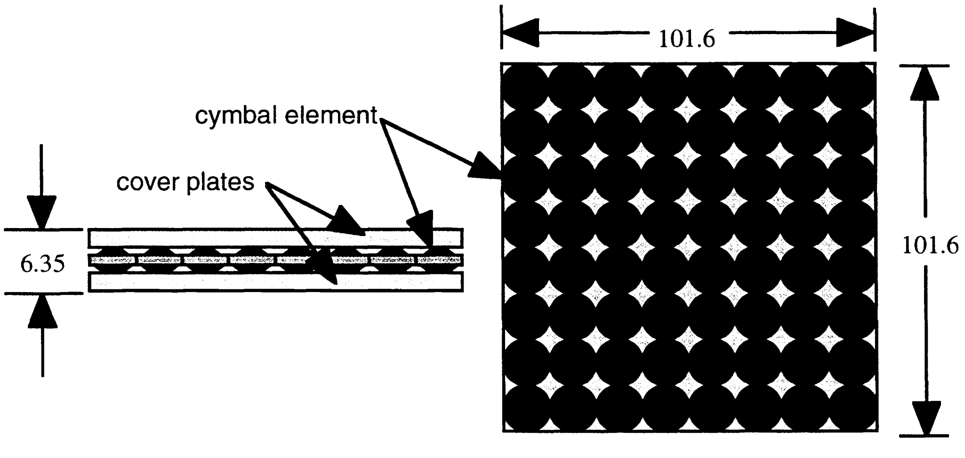


Figure 6: Side and top views of cymbal driven projector panel (dimensions in mm)[13].

2.3 In-air Evaluation

In-air displacement measurements were made using a Vibration Measurement System (Model 1941), which is a non-contact system for detecting, monitoring, and measuring vibrations. Based on laser Doppler velocimetry (LDV) technology, the system operates by scattering monochromatic light from the surface of interest and measuring the Doppler shift of the light frequency caused by the motion of the surface. The shift is proportional to the surface velocity and consequently the surface displacement. The accuracy of the system is ± 0.4 dB. During LDV measurements, the bottom surface of the projector panel is rigidly clamped to a vibration isolation table which constitutes a fixed-free boundary condition. The panel is then driven with a sinusoidal signal of 1 Volt (rms) over a frequency span 100 Hz to 10,500 Hz with measurements made at 900 discrete frequency points in a 30 X 30 square matrix over the piston-like radiating surface of the panel.

The average spatial displacement over the surface of the actuator panel as a function of drive frequency is shown in figure 7. The modal peaks from this measurement are considerably lower than previous in-air immitance resonance frequency characterization (from 950 Hz to 383 Hz) because in the LDV study, the rigid bonding of the bottom panel surface apparently introduces the mass of the backing plate (i.e., the table) into the total transducer structural response. Consequently, the resonance frequency decreases rather than increases as one would expect from a rigid backing condition.

The vertical axis of figure 7 is the displacement value in units of dB reference 1 picometer for a 1 Volt drive (which is analogous to an effective piezoelectric charge constant d_{33}). For typical DoD Type VI piezoceramics, the displacement for a 1 Volt drive condition are on the order of a constant -185 to -190 dB//1 picometer/V. As demonstrated in figure 7, the cymbal driven panel is over 60 dB greater at its resonance frequency peak of 1.5 kHz and more than 30 dB greater in its pure piston mode below this frequency.

2.4 In-water Transducer Configuration

Previous to NRL's interest, underwater study was done at The Pennsylvania State University where the research concentrated on the cymbal element as a stand alone acoustic projector or a nodally mounted group of elements in an array configuration[14, 15]. The resonance of a single element cymbal driver was found to be 18 kHz while for a 3 by 3 nodally mounted array, the resonance frequency stayed approximately the same but instead of the expected higher frequency rolloff in TVR, the array configuration was shown to stay approximately constant.

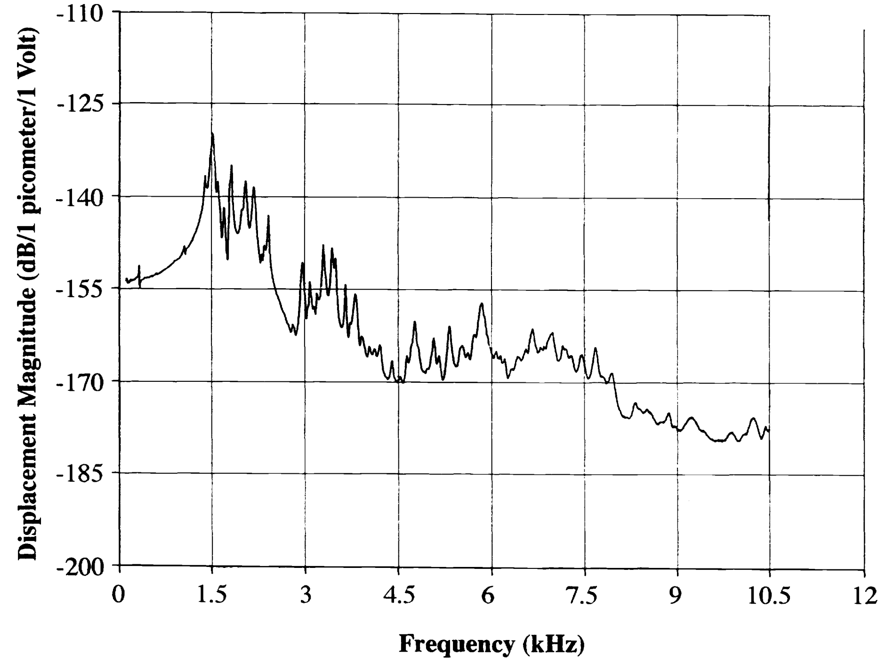


Figure 7: In-air cross-sectional average displacement magnitude profile of the cymbal panel driven with 1 Volt.

The NRL intention has been to load the cymbal element drivers in the sandwich arrangement such that the complete transduction device will feature a resonance frequency that is an order of magnitude lower. The actual arrangement is similar to the concept of the 1-3 piezocomposite materials in that instead of individual piezoceramic rods being driven in parallel, the individual cymbal elements will drive the panel as shown in the concept drawing of figure 6. The in-air panel data of figure 7 suggested that the lower frequency panel resonance frequency is possible in an in-air environment but to move this panel to an underwater environment means that the panel must be encapsulated and yet still be functional to flexing its cover caps in an unrestrained manner.

The panel used for the in-air study was first wrapped with a plastic wrap in order to maintain the interior air pocket and thus maintain the unrestrained cymbal element flexures. Once preshrink wrap was applied and a cable connector soldered to the outer plates, the panel was potted with a polyurethane encapsulant.

2.5 In-water Transducer Calibration

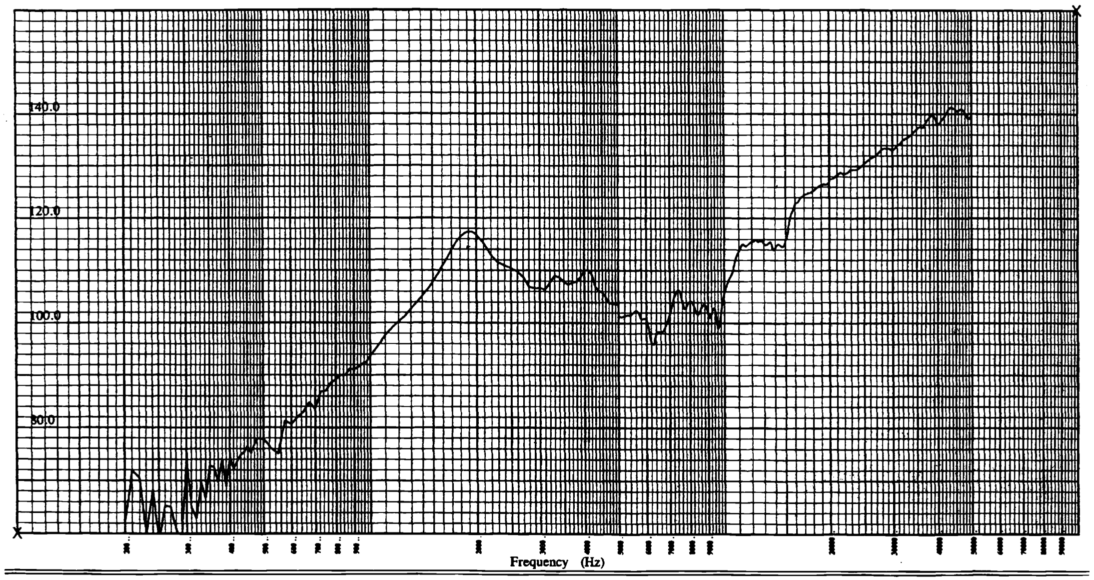
Once encapsulated, the cymbal panel was brought to the Naval Surface Warfare Center, Crane Division (NSWC/Crane) Glendora Lake Facility in Sullivan, IN for acoustic transmit calibration. Measurements were conducted over the frequency band of 200 Hz to 50 kHz with three different frequency sweeps. Figure 8 shows the composite transmitting voltage response (TVR) where each of the sweeps showed overlap agreement.

As desired, an overall panel resonance frequency was shown to occur at 1.9 kHz followed by a flexural resonance at 50 kHz. The 1.9 kHz resonance frequency is very exciting since this panel is only 6.35 mm thick and yet this transmit level suggest that source levels on the order of 180 dB can be expected at this frequency. Figure 9 shows a TVR for a 1-3 piezocomposite material with the same dimensions and mounted in the same manner. Note that for the 1-3 piezocomposite material the resonance frequency is at 150 kHz with a TVR level of 96 dB re 1 μPa/V @ 1 m at 1.9 kHz as compared with the cymbal panel of 118.6 dB re 1 μPa/V @ 1 m at this same frequency. Also note that the mechanical quality factor of this resonance frequency is less than 1.5 which is considerably lower than traditional flexural transducers and suggest that broadband algorithms may be considered in this lower frequency region on a mobile platform.

TEST
Transmit Voltage Response TVR (dB//uPa/V)

CUSTOMER NRL		PRESSURE 10.8 PSIG	DATE 12/15/1998 TIME 09:22:31
TEST ITEM CYMBAL PROJECTOR		TEMPERATURE 11.2 Deg C	PROJECT G9018
SERIAL NO. 8X8C1	Misc (Test Distance, Cable Length,etc) 3.8 Meters 30 M (F-42A)	MATCHING IMPEDANCE	SWEEP Cn0017.swp /0021/0022

Data @ 178 deg.



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Glendora Test Facility

Figure 8: Measured cymbal panel TVR (in units of dB re 1 μPa/V @ 1 m) versus frequency.

NAVAL UNDERSEA WARFARE CENTER
UNDERWATER SOUND REFERENCE DETACHMENT
P.O. BOX 568337, ORLANDO, FLORIDA 32856-8337

USRD NO. 0727-56
ANECHOIC TANK FACILITY
JAN 1996

TRANSMITTING VOLTAGE RESPONSE

Piezocomposite Transducer Serial 4-50
Pressure at one meter per volt applied at end of cable; Unbalanced
Water Temp: 22° C

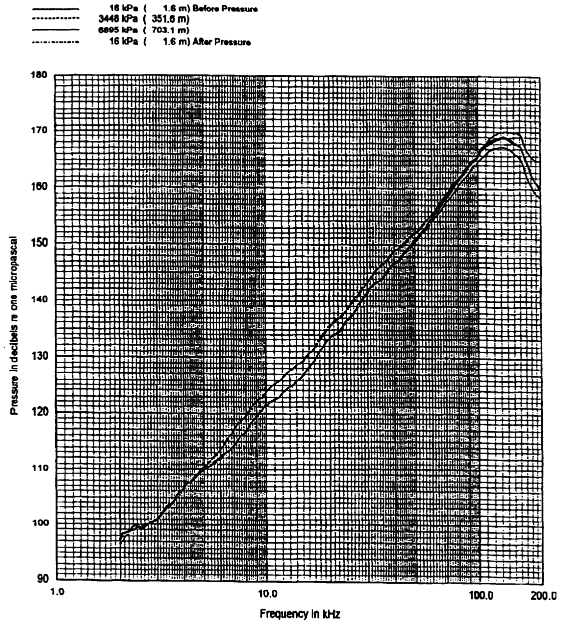

Figure 9: Measured 1-3 piezocomposite material TVR (in units of dB re 1 μPa/V @ 1 m) versus frequency for the same geometry as the cymbal panel of figure 6.

3. FUTURE RESEARCH DIRECTIONS

Comparisons of figures 8 and 9 also demonstrate the two distinct research paths being followed in the development of advanced AUV projectors. Figure 8 shows a busy modal activity response with a desirable low frequency resonance while figure 9 shows a broad, mode free response ideal for middle frequency, wide band responses. Both of these approaches offer new tools for the system designers to incorporate advanced algorithms in AUV and UUV sonar platforms.

Future research directions include the recent introduction of larger thicknesses of 1-3 piezocomposite materials. What this means is that the larger thickness will result in devices with lower resonance frequencies and thus can provide higher transmitting responses at the lower part of the operating bands while maintaining the mode free wide band performance.

The cymbal element driver panels are being further refined to deliver higher output at even lower frequencies. Current research is ongoing in the multilayering of the cymbal drivers such that higher output may be realized with relatively small increases in the final device thickness.

CONCLUSIONS

For application needs requiring acoustic projectors in the upper frequency band, 100 kHz to $\geq$1 MHz, there are many transduction devices and technologies available such that systems operating in these regions have a variety of possibilities with other piezocomposite material configurations[16] and polyvinylidene fluoride (PVDF)[17] materials and devices. However the need for wide band acoustic projectors operating in the middle frequency regions is being addressed with advanced 1-3 piezocomposite material based transducer designs. The development of low frequency, thin profile, acoustic projectors is being addressed through the development of cymbal based driver panels. Early indications are that these panels can meet the frequency and transmit levels desired for the AUV and UUV based sonar platforms.

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