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A Comparison of the Underwater Acoustic Performance of Cymbal-Based Projectors to 1-3 Piezocomposite Materials

JAMES F. TRESSLER[1,*] & THOMAS R. HOWARTH[2]
[1]*Naval Research Laboratory, Washington, DC 20375-5350, USA*
[2]*Naval Sea Systems Command, Division Newport, Newport, RI 02841-1708, USA*

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Abstract. The performance of two different 'cymbal' actuator-based underwater acoustic projector designs is compared. One projector design is a 101 mm by 101 mm Thin Panel potted in polyurethane. The other is a 152.4 mm by 76.2 mm tungsten-backed flat panel embedded in a syntactic foam frame. Both projector designs are characterized in-air and evaluated in-water. The results of the in-water studies are based on a 100 Watt power supply. Comparing to 1-3 piezocomposite materials with the same radiating area and similar thickness, these cymbal-based projectors appear to be best suited for use at frequencies below 4–5 kHz, with particular emphasis in the 1 kHz range. The cymbal-based devices described in this study are strictly prototypes and are not designed for a specific application. Nevertheless, the results indicate that if the acoustic aperture of these projectors were scaled to the appropriate dimensions, they could meet the design goals of many low frequency Navy applications where source levels >180 dB from a thin package are desired

Keywords: piezoceramic, 1-3 piezocomposite, cymbals

1. Background

The U.S. Navy is currently interested in the development of low frequency (<10 kHz) acoustic source (projector) technology for use on smaller, unmanned underwater vehicles that operate in a shallow water environment [1, 2]. Among the desired projector attributes are low volume occupation along with specific acoustical and electrical requirements. Acoustically, the desire is for high sound output (>180 dB), while geometrically they need to be thin (<60 mm) for installation onto the sides of a 50 cm diameter vehicle. The electrical requirements are such that the input power cannot exceed the vehicle power delivery limitations, which is typically 100 Watts for a SONAR payload.

Conventional low frequency source technologies, such as flextensional transducers, tonpilz projectors, free-flooded piezoelectric ceramic rings, and electromagnetic drivers [3, 4] are not easily adaptable for mounting on small vehicles because of their large size, weight, and difficulty in aperture control. Piezoceramic-polymer composites, although meeting the dimensional requirements, have a lower acoustic output below 10 kHz than desired [5, 6].

Consequently, the Naval Research Laboratory has been developing 'cymbal'-based acoustic projector panels as low frequency underwater acoustic sources. This paper will discuss two cymbal-based projector designs that demonstrate the feasibility of this technology for use below 10 kHz.

2. Single Element Cymbal Drivers

The two projector designs described in this paper utilize so-called 'cymbal' actuators [7, 8] as the driver elements. In both designs, an array of single element cymbals pushes on a stiff cover plate which, in turn, serves as the source of the low frequency sound. The mechanism is discussed in more detail later. This section will focus on single element cymbal drivers themselves,

*To whom all correspondence should be addressed.

particularly on the geometry of the elements, their in-air characteristics and their performance underwater. The single element data will help to explain the need to incorporate them into array/panel configurations.

2.1. Geometry

A cymbal actuator consists of a piezoelectric ceramic disk sandwiched between and mechanically bonded to two thin metal caps. Each cap is shaped in a die press so that it contains a shallow air cavity underneath its inner surface after it is bonded to the face of the ceramic disk. The caps serve as mechanical transformers for converting the small radial displacement and vibration velocity of the piezoelectric disk into a much larger axial direction displacement and vibration velocity perpendicular to the apex of the caps. Hence, the cymbal driver primarily utilizes the d_{31} contribution of the active ceramic to achieve flexure in the caps. The resonance frequency of the radial mode of the ceramic disk is roughly ten times that of the operational frequency. Hence, the cymbal element is operated well below the first ceramic resonance.

A side view sketch of the geometry of a cymbal element used for this study is shown in Fig. 1. Cymbals with two different diameters (designated as CymDia-1 and CymDia-2) were used. Table 1 lists their respective dimensions. Titanium was selected as the cap material

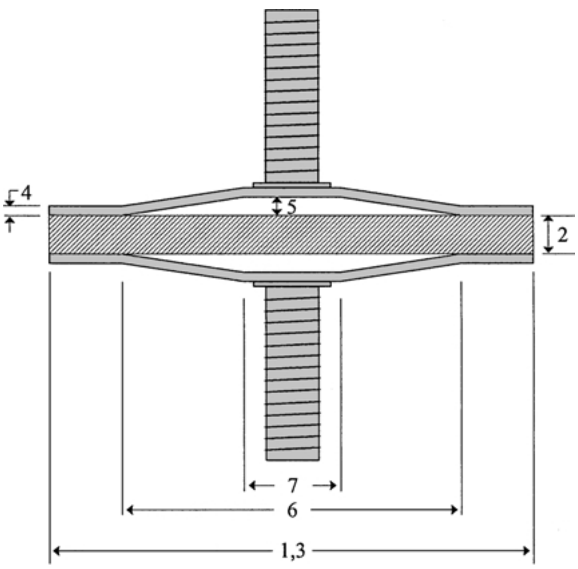


Fig. 1. Cross-sectional schematic of a cymbal element with threaded studs. Dimensions are provided in Table 1.

Table 1. Dimensions of the cymbal drivers.

	Parameter	Dimension (mm)
CymDia-1	1 – Ceramic diameter	12.7
	2 – Ceramic thickness	1.0
	3 – Cap diameter	12.7
	4 – Cap thickness	0.25
	5 – Cavity depth	0.28
	6 – Cavity diameter	9.0
	7 – Cap apex diameter	3.0
CymDia-2	1 – Ceramic diameter	15.875
	2 – Ceramic thickness	1.0
	3 – Cap diameter	15.875
	4 – Cap thickness	0.25
	5 – Cavity depth	0.28
	6 – Cavity diameter	12.0
	7 – Cap apex diameter	3.0

because of its low density, moderate elastic modulus, electrical conductivity, and oxidation resistance. These factors combine to provide a preferred leverage of low frequency flexural resonance and an appropriate balance of force and displacement that allows for operation at water depths of less than 30 meters. Prior to bonding the caps to the ceramic, 1.4 mm diameter studs that were 4.6 mm long with UNF 0-80 threads were welded to the apex of the caps.

The piezoelectric material used was PZT-5H (aka Navy Type VI) piezoelectric ceramic. This material was selected because its high piezoelectric d_{31} coefficient, which is nearly twice that of PZT-4 (Navy Type I) and 2.5 times greater than that of PZT-8 (Navy Type III), served to generate the largest flexure (i.e., displacement) in the caps. The downside of using PZT-5H piezoelectric ceramic is that it has a relatively high electrical dissipation and can be depoled if driven too hard. However, for this application, the voltage drive levels and dissipation were considered suitable and the level of acoustic output is within the means of this material selection.

2.2. In-Air Characteristics

Typical in-air impedance versus frequency curves for the CymDia-1 and CymDia-2 cymbals in the neighborhood of their fundamental resonance are compared in Fig. 2. These measurements were conducted with the cymbal elements mounted in a free-free condition.

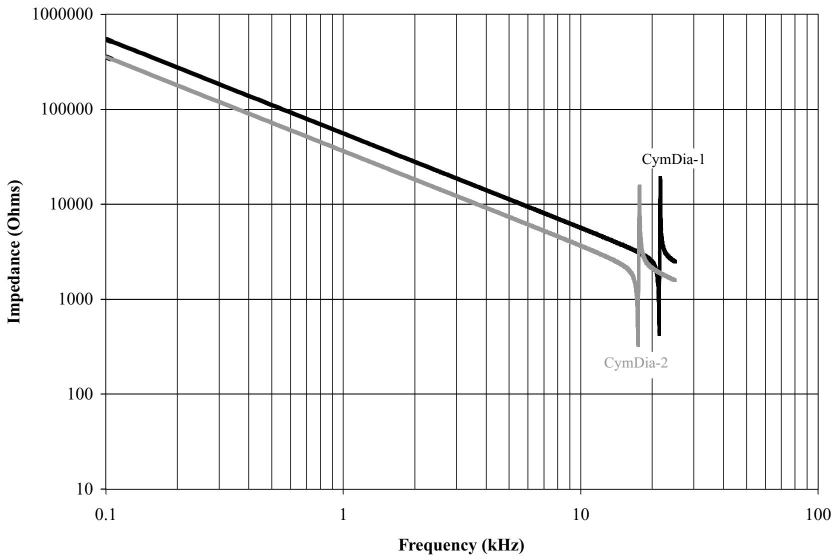


Fig. 2. Comparison of the in-air impedance spectra of CymDia-1 and CymDia-2 single element cymbals.

The fundamental resonance of a cymbal element comes from the flexural, or 'umbrella', vibration mode of the caps [9]. The CymDia-2 cymbal has a lower resonance frequency than the CymDia-1 cymbal because of its larger diameter. In addition to its diameter, the materials properties and geometry of the caps also govern the resonance frequency, the displacement (velocity) and force of an individual cymbal element [9]. The lower impedance of CymDia-2 as compared to CymDia-1 is associated with the larger ceramic area of CymDia-2.

2.3. *In-Water Evaluation*

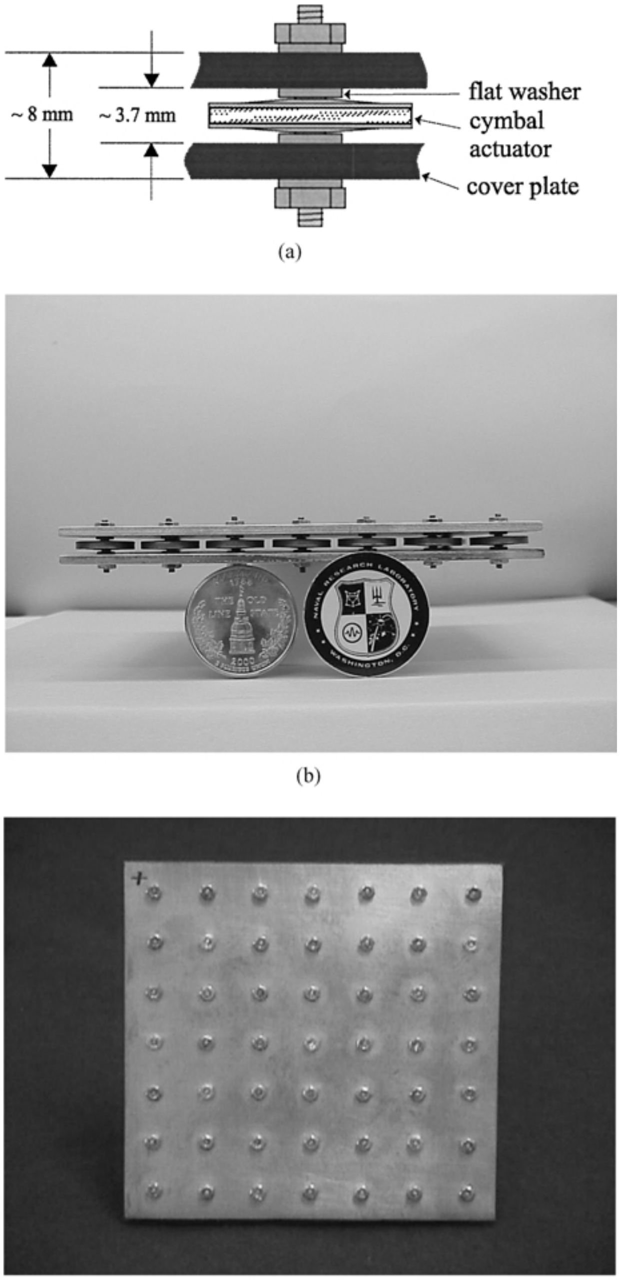
The transducer calibration data reported in this study are acoustic source level as well as electrical impedance and phase, all as a function of frequency. Acoustic source level is the acoustic output that is generated by the projector one meter from its face. It is reported in terms of decibels, with an acoustic reference level of 1 μPa.

The underwater acoustic characteristics of single element cymbals have been previously reported [10, 11]. Each cymbal was nodally mounted along its outside rim in a rubber o-ring fixture that was sealed in an oil-filled boot. This mounting configuration allowed both the front and back caps to flex freely. Electrical contact was made to the piezoceramic disk via the studs on the metal caps.

For a duty cycle of a few percent, the 1 mm thick PZT-5H piezoelectric ceramic in a cymbal can withstand an input voltage of approximately 500 Volts (throughout the text, Volts implies V_{rms}). Higher drive voltages may either cause depoling or hysteretic non-linear effects. Based on this drive level, a 12.7 mm diameter single element cymbal can generate a source level on the order of 170 dB, but only over a narrow frequency band (7–7.5 kHz).

2.4. *Arrays*

Because the acoustic output of a single cymbal element is too low and too narrow band for most applications, an array of cymbal actuators was used to drive a stiff cover plate in a panel configuration. An array of elements will boost the acoustic source level by increasing the radiating area of the projector. The cover plate serves two purposes. One is to provide a uniform displacement profile across the radiating surface. The second is to additionally mass load the individual cymbal drivers, thus reducing their resonance frequency [12]. The lowest resonance is achieved through the combination of mass loading by the medium, mutual impedance and load coupling and more generally, the flexural resonance of the individual cymbal elements. This low frequency resonance achieved by the loading is several orders of magnitude less than the radial mode of the



(c)

Fig. 3. Cymbal-based Thin Panel-I projector showing (a) a close-up sketch of a cymbal element in the Panel, (b) the view from the side, and (c) the view from the top.

piezoelectric disk by itself and an order of magnitude less than that of a single cymbal element.

Two different projector designs were investigated, one was a Thin Panel and the other was as a direct plug-in replacement for a 1-3 piezocomposite-based projector used in a synthetic aperture SONAR (SAS) application. Since this study was focused on a specific vehicle that is used in shallow depths (<30 meters), there was no design objective to design these panels for hydrostatic pressure independence. A previous study

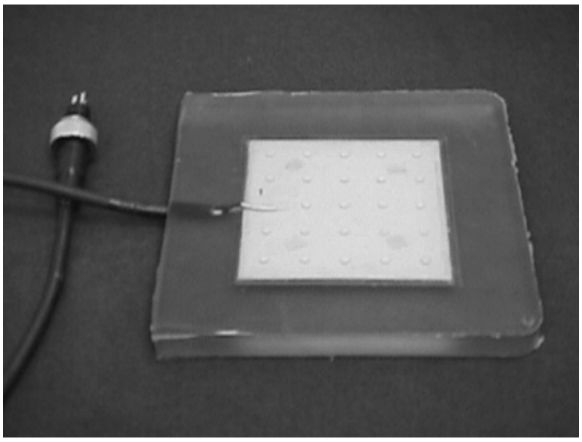


Fig. 4. A cymbal Thin Panel potted in polyurethane.

[13] has shown that no significant change in performance is seen when operating the cymbal at these shallow depths.

3. Thin Panel Projectors

3.1. Design

The cymbal Thin Panel design had a radiating area of 101.6 mm by 101.6 mm and a thickness, prior to potting, of approximately 8 mm. This projector design consisted of an array of individual cymbal actuators sandwiched between two 2.2 mm thick carbon graphite epoxy cover plates (solid all uni-carbon from Aerospace Composite Products, San Leandro, CA). The outer surfaces of the epoxy boards were electroplated with copper while the undersides were covered with electrically insulating Kapton® tape. The electrical connection from the copper plating to the piezoceramic disk was made through the stud, nut, titanium cap, and conductive adhesive.

Two panels, designated as Thin Panel-I and Thin Panel-II, were built and tested. Thin Panel-I consisted of forty-nine CymDia-1 cymbal actuators in a 7 by 7 arrangement. Thin Panel-II contained twenty-five CymDia-2 cymbal drivers in a 5 by 5 configuration. In both the Thin Panel designs, the array of single element cymbal actuators were electrically connected in parallel.

The top and bottom cover plates were torqued onto the studded cymbals with hex nuts. Top and side views of Thin Panel-I are shown in Fig. 3. Prior to being potted, a polyurethane gasket was wrapped around the outside edges of the panel in order to maintain the pocket of air within the cymbal matrix after it was potted. The completed panel, after the cable was attached and the device was potted in polyurethane, is shown in Fig. 4.

3.2. In-Air Characteristics

Figure 5 shows the impedance spectra of Thin Panels I and II, as measured in-air, through their respective

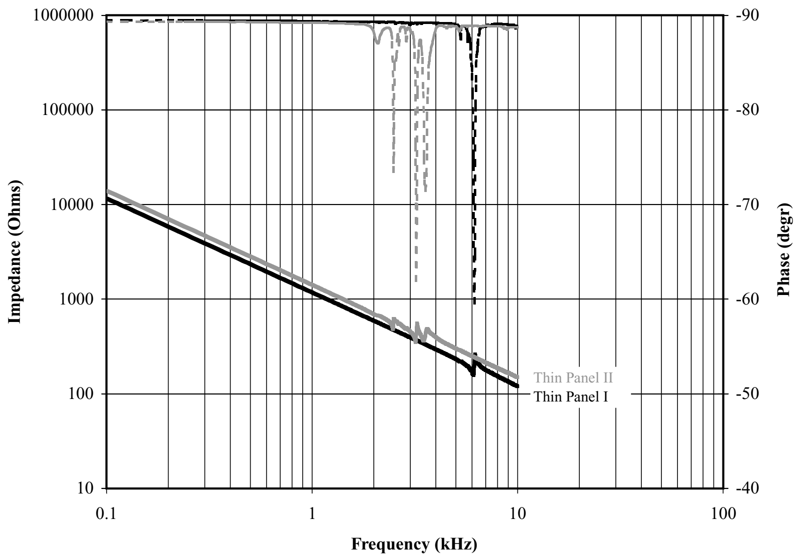


Fig. 5. In-air impedance spectra of Thin Panels I and II.

Table 2. Capacitance values of the cymbal Thin Panel projectors.

Projector	Capacitance (nF)	tan δ	Ceramic area (m^2)
Thin Panel-I	140	0.016	0.00621
Thin Panel-II	114	0.016	0.00495

fundamental resonance frequencies. Thin Panel-I has a clean fundamental resonance at around 6 kHz, whereas Thin Panel-II exhibits multi-mode resonance behavior over the frequency range of 2.5 kHz to 3.5 kHz. This multi-mode behavior in Panel-II is attributed to the doubly resonant behavior often seen in the individual 15.875 mm diameter cymbals. This double resonance is due to a mechanical coupling between the fundamental flexural mode of the metal caps and an induced bending mode in the piezoelectric ceramic disk [14]. The lower resonance frequency of Thin Panel-II as compared to Thin Panel-I arises from a combination of factors. The primary reason is due to the larger diameter of the CymDia-2 cymbal used in Panel-II. In addition, there is a greater mass loading on each of the CymDia-2 cymbals in Panel-II than on the CymDia-1 cymbals in Panel-I due to the fewer number of cymbals in Panel-II carrying the load of the cover plate. As compared to a single element (Fig. 2), the impedance drops by a factor equal to the number of cymbal drivers in the respective Thin Panel design.

The room temperature capacitance and dielectric loss (both measured at 1 kHz) of the two Thin Panel projectors are listed in Table 2. The ratio in capacitance between Thin Panel-I and Thin Panel-II is directly proportional to the ratio of ceramic area between the two panel types.

3.3. In-Water Evaluation

Figure 6 compares the untuned acoustic source levels attained by Thin Panels I and II for a maximum input power of 100 Watts coupled with a voltage limitation of 500 Volts. The source level of a single element cymbal (CymDia-1), as discussed in Section 2.3, is shown for comparison. The Thin Panels exhibit very low in-water resonance frequencies: 1.3 kHz for Panel-I and 0.75 kHz for Panel-II. The in-water resonance frequencies of the panels are lower than what was measured in-air because of the additional mass load of the water. A 1-3 piezocomposite, with the same dimensions as the cymbal-based Thin Panels, exhibits its fundamental in-water resonance frequency at about 100 kHz [5].

The electrical impedance of Thin Panels I and II, when submerged in water, is shown in Fig. 7. The

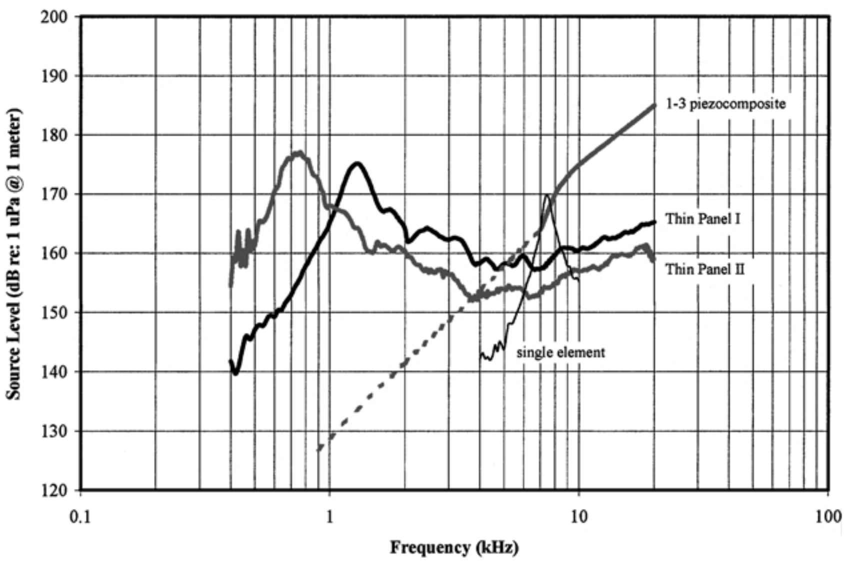


Fig. 6. The acoustic source level generated by Thin Panels I and II from a 100 Watt power source. The source level of a single element cymbal and a same-size 1-3 piezocomposite material are also shown for comparison.

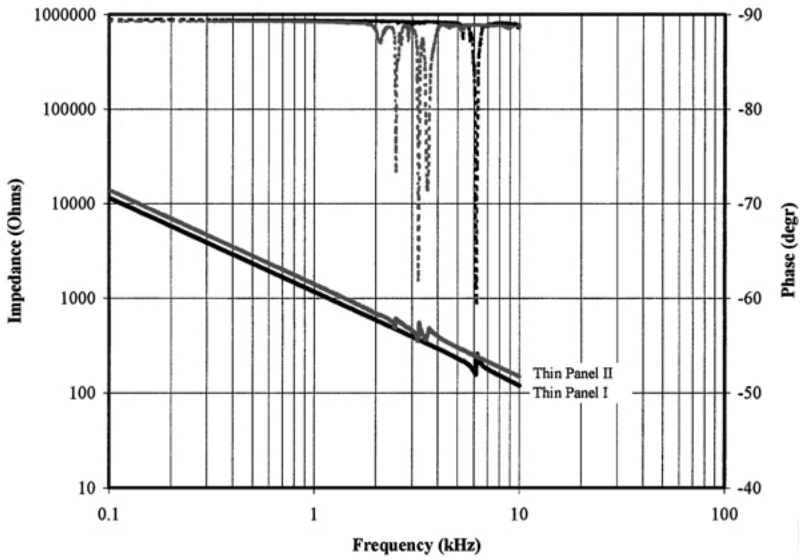


Fig. 7. Comparison of the in-water impedance spectra of Thin Panels I and II.

difference in impedance between Panels I and II is due to the difference in ceramic area between the two panels. No significant change in impedance is observed in the vicinity of the respective panel resonance frequencies. Likewise, there is very little change in the phase. In addition, there is essentially no difference between the impedance amplitudes when measured in-water or in-air (from Fig. 5).

Based on previous studies [5], the source level achieved by a 1-3 piezocomposite with the same dimensions as the Thin Panels was calculated and is shown in Fig. 6. The measurements were suspended below 7 kHz, so the dashed line in this plot is extrapolated data. The calculation is based a 100 Watt power source and a maximum drive level of 157.5 Volts/mm [15]. The discrepancy in drive level limitations from the cymbal to the 1-3 piezocomposite is attributed to the lack of preload in the cymbals as well as their superior thermal dissipation capacity. The Thin Panels start to show higher acoustic output than the 1-3 material at frequencies below 4–5 kHz. In the neighborhood of and below the Thin Panel resonance frequencies, the source level is expected to be nominally 35–40 dB greater than that of a 1-3 piezocomposite. Although the 1-3 material exhibits a higher source level than the cymbal panels from 4–5 kHz to 10 kHz, the Thin Panels would be capable of achieving source levels exceeding 180 dB through proper design engineering.

4. SFH Projector Panels

4.1. Design

This cymbal-based projector was designed as a direct plug-in replacement for a 1-3 piezocomposite-based projector mounted in a syntactic foam housing [6, 16]. Two cymbal-based transducers, designated as CSFH-I and CSFH-II, were built and tested. Both had a radiating area of 152.4 mm by 76.2 mm. CSFH-I consisted of fifty CymDia-1 cymbal drivers in a 10 by 5 arrangement. CSFH-II contained thirty-two CymDia-2 cymbals in an 8 by 4 configuration.

In this projector design, the array of cymbal drivers was sandwiched between a 12.7 mm thick tungsten backing plate and a 2.2 mm thick copper electroplated carbon graphite epoxy board (Fig. 8). Ideally, the tungsten backing plate would serve as an acoustically hard boundary condition behind the layer of cymbals. However, this condition is certainly frequency dependent below 20 kHz, and thus for this design the condition is partially compromised. As opposed to a soft acoustic backing such as air, theory dictates that the source level should be enhanced by 6 dB if a perfectly rigid boundary condition is imposed behind the active layer [17]. In practice, the enhancement is reduced to 3 to 4 dB between 10 kHz to 20 kHz and then gradually rises to over 5 dB at 100 kHz. Below 10 kHz, however, the effect is essentially negligible. In the case of the

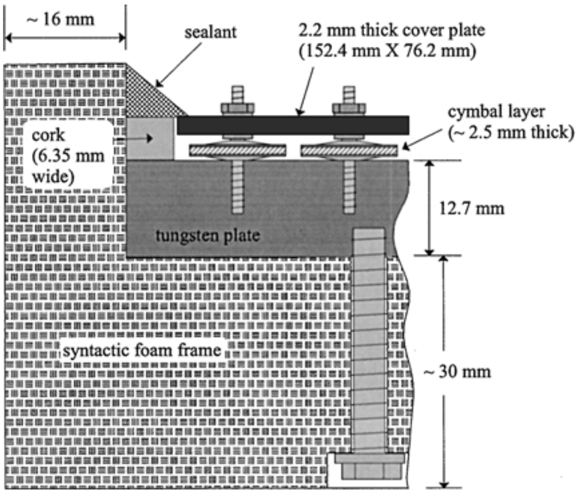


Fig. 8. Side view cutaway sketch of a CSFH projector.

cymbal-based design, the tungsten serves as a source of ballast and mass loading.

The studded cymbals were initially torqued into a predrilled and threaded tungsten backing plate, as seen in Fig. 9(a). Next, a drilled out graphite cover plate (with Kapton® tape on the underside) was lowered into place so that it rested over the top of the cymbal array. The cover plate was similarly torqued onto the studded cymbals with hex nuts (Fig. 9(b)). The bottom of the projector assembly (i.e., the tungsten backing plate) was then bolted to the inside of a syntactic foam frame, where the bolts doubled as the ground electrodes. Between the outside edges of the projector assembly and the inside of the syntactic frame was a 6.35 mm wide strip of corprene (cork). This material behaves as an acoustically soft boundary, which results in a pressure release condition that is used for decoupling of lateral acoustic pressures. The thin gap between the corprene and the top surface of the graphite cover plate was covered with a polythioether polymer-based sealant. This was done to prevent liquid polyurethane from seeping into the air cavity within the cymbal matrix during the potting process. This sealant was sufficiently compliant so as not to impede the movement of the edges of the cover plate during operation.

As in the case of the Thin Panel design, the single element drivers in the CSFH projectors were connected electrically in parallel. To ensure that the electrical connections could withstand a high voltage level, four separate positive connectors were soldered to the top of the cover plate. These leads were channeled through the interior of the syntactic frame so that they could be addressed at the back of the transducer via Bratner SEA-CON XSA waterproof connectors.

Figure 9(c) shows the completed cymbal transducer assembly prior to encapsulation in polyurethane. In practice, only the top surface of the projector would be covered in polyurethane, Fig. 9(d). However, for test purposes and to insure no water leaks would occur, the entire transducer assembly was encapsulated with polyurethane.

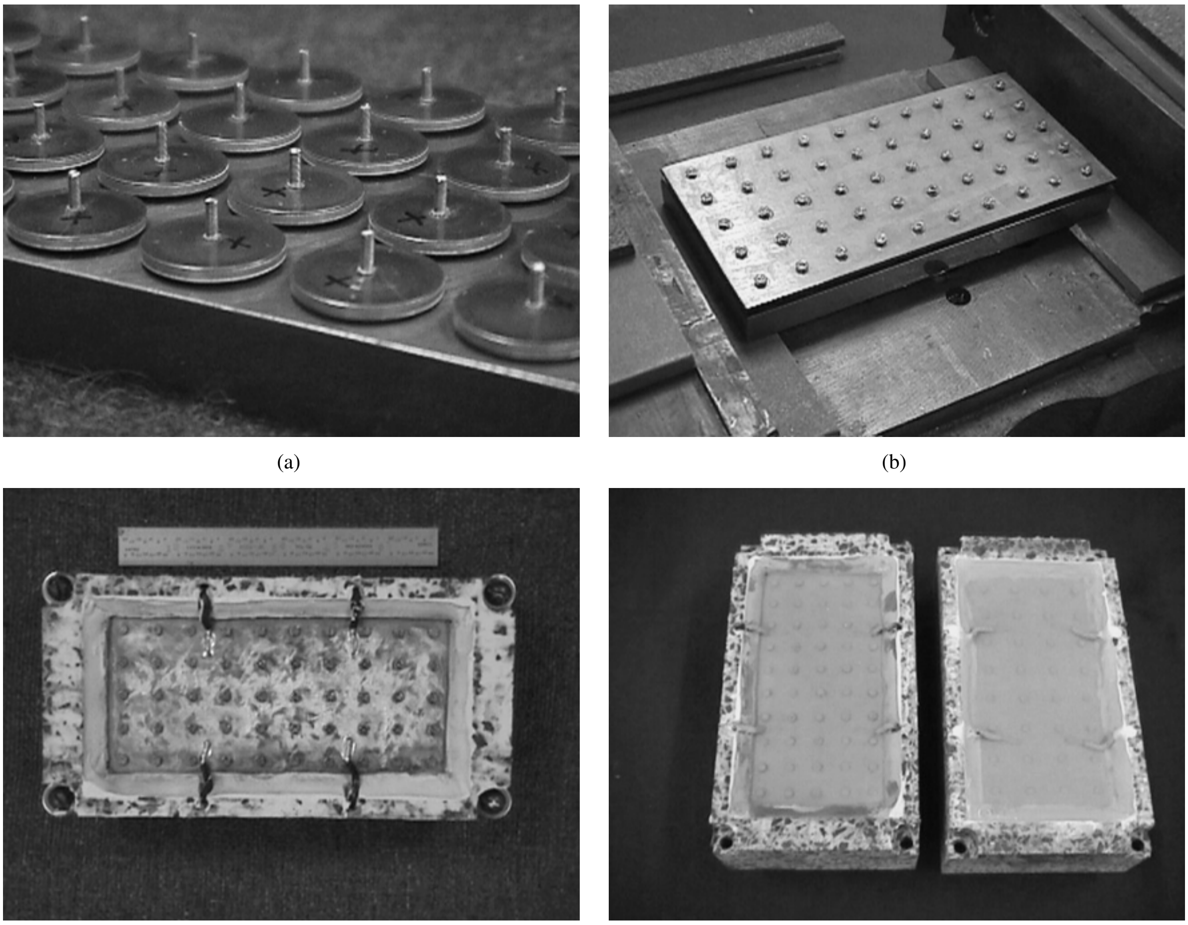
4.2. *In-Air Characteristics*

The in-air impedance spectra of the two CSFH projectors are compared in Fig. 10. The in-air resonance frequencies of CSFH projectors I and II are 1.6 and 1.3 kHz, respectively. The difference in their resonance frequencies is again due to the different diameter cymbal drivers. The area of ceramic in the two CSFH transducers is the same. This accounts for the off-resonance overlap in their impedance curves. As compared to a single element (Fig. 2), the impedance drops by a factor equal to the number of cymbal drivers in the respective CSFH design. The rather marked difference in resonance frequencies between this transducer design and the cymbal Thin Panel design is associated with the additional mass loading effect of the tungsten backing plate and the passive components such as the urethane.

The room temperature capacitance and dielectric loss (both measured at 1 kHz) of these two transducers are given in Table 3. The capacitance values are practically the same (within two percent), as would be expected since the area of ceramic in both transducers is identical. The capacitance measured for these transducers, however, is higher (and the loss lower) than that measured for Thin Panel I, which contains nearly the same ceramic area. The difference is attributed the reported capacitance values of the CSFH projectors being measured very close to their respective resonance frequencies.

Table 3. Capacitance values of the cymbal SFH projectors.

Projector	Capacitance (nF)	tan δ	Ceramic area (m^2)
CSFH-I	151	0.014	0.00633
CSFH-II	154	0.014	0.00633



(a) (b) (c) (d)

Fig. 9. Assembly procedure for a CSFH projector showing (a) the cymbal elements torqued into the tungsten backing plate, (b) the sub-assembly with the cover plate in place, (c) the sub-assembly in the syntactic foam frame prior to potting, and (d) the finished projectors CSFH-I and CSFH-II.

4.3. In-Water Evaluation

The electrical impedance of CSFH Projectors I and II, when submerged in water, is shown in Fig. 11. Because there is no difference in ceramic area between the two CSFH projectors, the impedance curves overlap. No significant change in impedance or phase is observed in the vicinity of the respective projector resonance frequencies. In addition, there is essentially no difference between the impedance amplitudes when measured in-water or in-air (from Fig. 10).

Figure 12 compares the untuned source levels obtained from CSFH Projectors I and II for a maximum input power of 100 Watts coupled with a voltage limitation of 500 Volts. The source level of a single element cymbal (CymDia-1), as discussed in Section 2.3, is shown for comparison. The CSFH Projectors exhibit very low in-water resonance frequencies: 0.9 kHz for CSFH-I and 0.6 kHz for CSFH-II. The in-water resonance frequencies of the projectors are lower than what was measured in-air because of the additional mass load of the water.

A 1-3 piezocomposite with the same acoustic aperture area but 12.7 mm thick and mounted in the same way in the same type of projector housing as the CSFH projectors exhibits a resonance at 8 kHz, which is a result of a strong device lateral mode [16]. The source level achieved by a 12.7 mm thick 1-3 piezocomposite

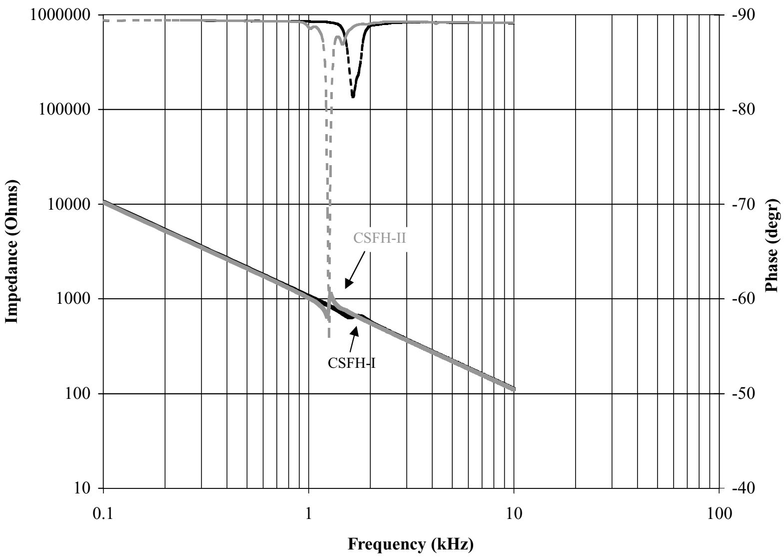


Fig. 10. In-air impedance spectra of CSFH-I and CSFH-II.

with the same radiating area as the CSFH projectors was calculated and is shown in Fig. 12. It assumes a 100 Watt power source coupled with a maximum drive level of 157.5 Volts/mm [15]. The calculation is based on previous experimental data [16]. There were no results reported below 4 kHz, so the dashed line in this plot is for extrapolated data. Only at frequencies below the crossover at 2–3 kHz are the CSFH projectors expected to show significantly better acoustic output than the 1-3 based design.

Figure 13 shows the source level of CSFH-I as a function of drive level in the neighborhood of its fundamental resonance frequency. A duty cycle of one percent was used as this was representative of the operational requirements. For this particular experiment, the 100 Watt power requirement was waived

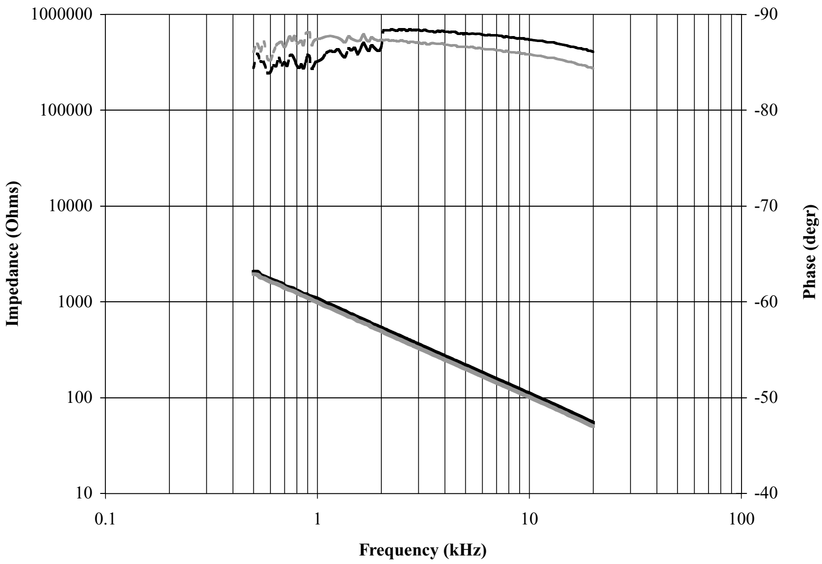


Fig. 11. In-water impedance spectra of CSFH-I and CSFH-II.

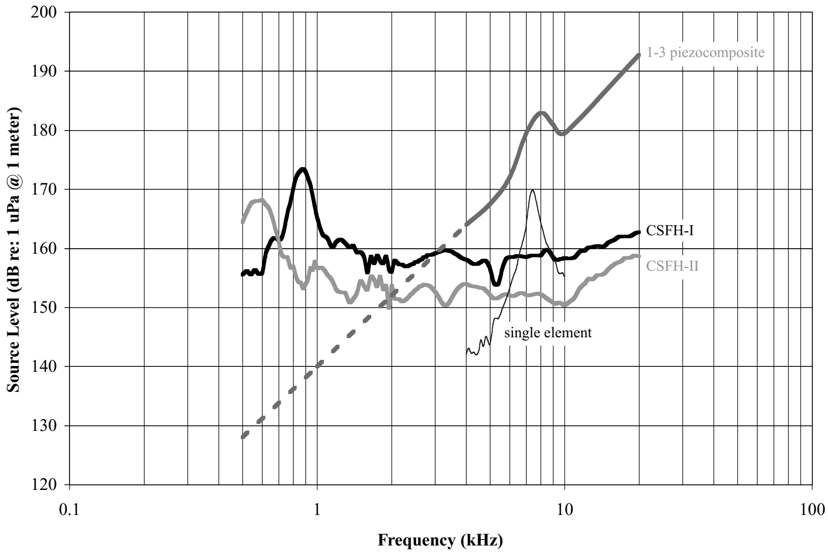


Fig. 12. The acoustic source level generated by CSFH-I and CSFH-II from a 100 Watt power source. The source level of a single element cymbal and a similar 1-3 piezocomposite material are also shown for comparison.

in order to ascertain some general high drive capabilities. Nonlinear behavior becomes apparent when the drive level exceeds 500 Volts. In order to prevent premature failure, the transducer was not driven beyond 750 Volts. Also shown in the figure (the gray curve) is the source level when re-driven at 100 Volts after having been driven at 750 Volts. The pre-750 Volt and post-750 Volt curves essentially overlap, indicating an absence of adverse effects on the transducer due to the high drive conditions. It should be noted that the CSFH-I projector was only driven at 750 Volts for a short time (<5 min). Additional study would be required to better quantify projector reliability.

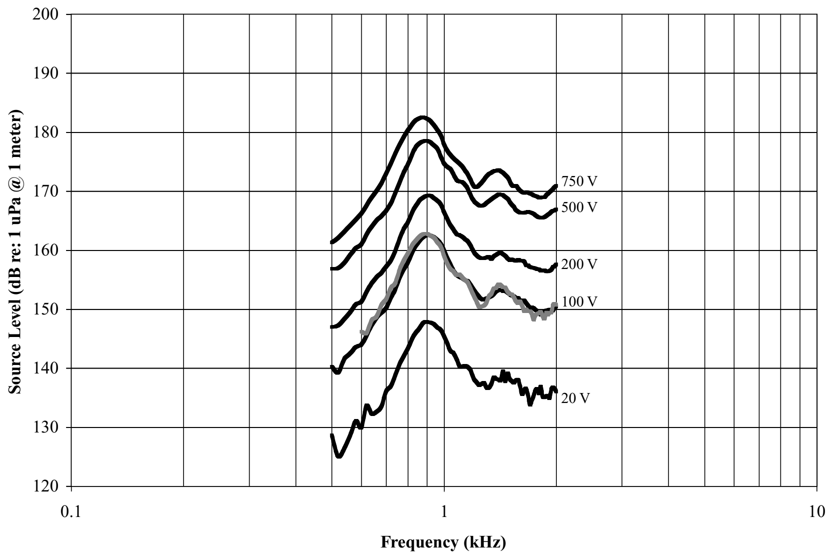


Fig. 13. The acoustic source level of CSFH-I in the neighborhood of its fundamental resonance frequency as a function of drive level.

5. Conclusions

Conventional 1-3 piezocomposite materials are aptly suited for many underwater projector applications when the intended frequency range is above 20 kHz. Between 10 kHz and 20 kHz performance compromises are required. The new cymbal-based projector designs show great promise for applications that require thin devices with suitable acoustic output where the intended frequency band is below 10 kHz. By combining both the cymbal Thin Panel and 1-3 piezocomposite panel designs on the same vehicle, the potential exists to cover a frequency band from 500 Hz to 200 kHz within a thin package that can be mounted onto smaller vehicles. This large an operating band thus offers the potential for multipurpose SONAR systems to be placed within the same packaging arrangement.

The cymbal-based projector designs described in this study demonstrate that low frequency operation is possible. However, the lower than desired acoustic output also suggests that further refinement of the cymbal-based projector approach is desired. For instance, to obtain source levels on the order of 180 dB or higher requires unacceptable drive levels for these particular transducers. Methods to improve the output include a larger cross-sectional area as well as improved acoustic output from the projector. The use of the tungsten backing plate did result in a significant lowering of the resonance frequency but it also restricted the delicate balance of force and displacement, which means that the final output was compromised. On-going studies are now concentrating on removing the backing mass as well as using oil-filled inner matrices for applications where greater depth performance and increased bandwidth are desired.

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