Broadband acoustic projector for low-frequency synthetic aperture sonar application

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ABSTRACT

Possibilities for increased mine detection and classification techniques have established a need for broadband, underwater acoustic projectors. An advanced version of a low frequency synthetic aperture sonar (SAS) for the mine reconnaissance hunter program has recently been developed. The transducer is resonant at 100 kHz but has been designed to deliver constant high sound pressure levels over an operating frequency range of 10 kHz to 100 kHz. This wide band operation is accomplished because of an absence of spurious modes within the operational frequency decade. The actual projector is constructed with a two layered 1-3 piezocomposite material stacked in mechanical series and electrically wired in parallel. This arrangement was selected in order to maximize the source level output. The center electrode of the monolithic 1-3 piezocomposite layers has been segmented to offer four individual elements such that combinations of the sectors offer the ability to access nine different apertures. A constant source level is maintained through the use of a preshaped transformer between the driver and the projector. The combination of the transformer design with the clean spectrum response of the composite material results in an acoustic projector with constant source level.

Keywords: piezocomposite, broadband, transducer, projector, multilayer, SAS, MR/H

INTRODUCTION

The Naval Research Laboratory (NRL) has completed the design, fabrication and initial in-water acoustic evaluation of a prototype underwater projector. This sound source has been designed for replacement of limited bandwidth tonpilz projectors presently placed on an autonomous underwater vehicle (AUV) mine reconnaissance hunter (MR/H)[1]. The NRL projector will be used in the present MR/H system to provide a decade long frequency sound source. The need for this broad frequency source is to increase present mine classification techniques. Recent underwater acoustics research interests have identified improved underwater acoustic minehunting capabilities by upgrading SONAR systems to broadband frequency operations. The advantage of operating over a wide band is to classify underwater targets by their specular acoustic resonant scattering signatures. This capability has theoretically shown benefit in improved imaging for underwater mine characterization and identification[2].

I. SYSTEM CONCEPT AND DESIGN

Current mine detection and classification systems use existing transducer designs, such as the tonpilz (piston) transducers. This type of transducer was originally designed for deep water application where high source level in a limited band is desired for long range detection and avoidance applications. However, in efforts to utilize existing transduction products, many current mine classification and detection systems continue to use tonpilz transducers because they are available "off the shelf," that is, the development expense of the tonpilz transducer has already been made. The tonpilz transducer featured in the low frequency synthetic aperture array (LFSAS) of the MR/H[1] was originally designed to provide a maximum source level at 20

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kHz with high efficiency and reliability as well as excellent directivity responses. The manufacturing of the tonpilz transducer is an expensive process since each element is manufactured through hand assembly. The pairing of each element is then placed into a final arrangement by matching the electrical and mechanical characteristics of each transducer such that a final array of elements is determined by a prescribed array configuration. This means that a number of extra tonpilz transducers are fabricated in order to do the element sorting. Because of the hand assembly and sorting, the final cost of a 2 by 4 array (8 elements) configuration is high. Furthermore, the utilization of this transducer comes at a performance cost in terms of operating frequency (20 kHz) and operating bandwidth (< 10 kHz). The tonpilz transducer has the advantage of high source level (> 220-dB at f_R) but in the shallow water environment of the MR/H, source level requirements greater than 210 dB are not desired because of the reverberant nature in the shallow water environment.

The AUV system configuration using the NRL projector has been designed for two horizontal acoustic beams (1 λ and 2λ apertures) in order to accomplish multi-aspect operation and acoustic motion compensation. These apertures have been selected so that the SONAR can realize a 3-inch resolution of the underwater structures[1]. The implementation of multioctave frequency systems have recently progressed with the introduction of new expanded digital electronic capabilities because these are able to handle large amounts of data for efficient processing in real time. However, the advancement of underwater sound projectors has typically been a limiting factor for realizing the potential system gains that the digital data processing schemes offer. Traditionally, underwater projectors have been used solely at their resonance frequency with a limited bandwidth of -3 dB about this frequency. This has resulted in projectors useable only at discrete frequencies with limited bandwidth. Although there are some electronic means for "tuning" projectors to behave with additional electrical resonance frequencies, this approach will often result in system instabilities in terms of the electrical impedance magnitudes and phase. These instabilities may introduce problems in terms of limitations with the data processing. A solution to this is the use of an acoustic projector capable of mode-free (no instabilities) decade frequency operation, however, the is no such a projector that can output a constant source level over this large a band.

A technique to accomplish the desired constant source level is to design a transducer free of spurious modes over the desired band where the transducer resonance frequency occurs at the upper frequency limit of the intended band. Since transducers typically rise at 12 dB/octave or 20 dB/decade[3], a transducer that is theoretically driven with a -20 dB/decade voltage response will produce a constant source level over the intended frequency band. Figure 1 shows the conceptual graph of this behavior where the input drive voltage is added to the transducer response to form a constant source level output over the frequency band of 10 kHz to 100 kHz.

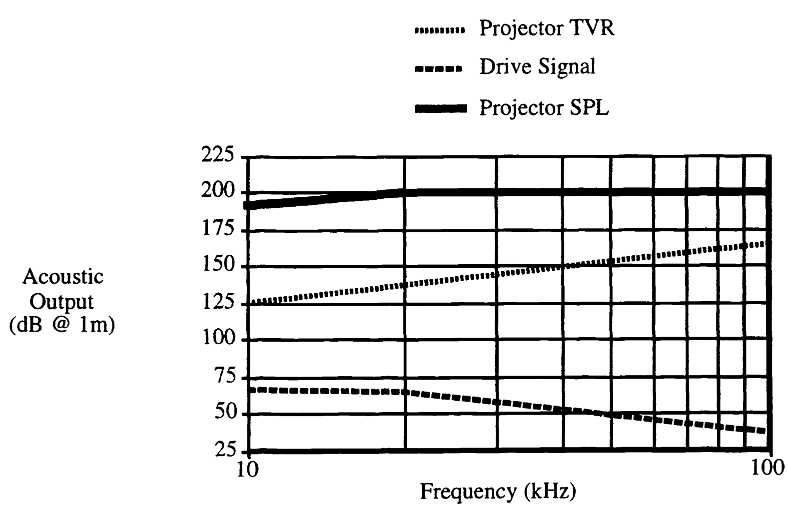

Figure 1: Conceptual graph of a means to realize constant source level.

II. NRL PROJECTOR DESIGN

The NRL underwater acoustic projector has been developed for the 10 kHz to 100 kHz frequency band displayed in figure 1. This band coverage will be used in a synthetic aperture SONAR (SAS) minehunting AUV, however, the design of this projector permit its use in other side scan and mine classification applications.

A set of system specifications and desirable features is presented in Table I. The specified operating band is over the figure 1 decade frequency range as opposed to the current MR/H discrete operation of the tonpilz approach. Also note that the source level is to be a minimum of 190 dB at 10 kHz and while rising to 200 dB at 20 kHz. The source level is then designed to be held constant at 200 dB from 20 kHz to 100 kHz.

TABLE I
Projector Performance Goals

Operating Frequency Band: 10 kHz to 100 kHz

Source Level (minimum at 10 kHz): 190 dB for full aperture

Source Level (from 20 kHz to 100 kHz): Constant 200 dB for full aperture

Linear electrical phase response over the operating frequency band

Projector Radiating Face (vertical by horizontal): $2\lambda \times \lambda$ = 6" by 3" (for full aperture)

Element Radiating Face (vertical by horizontal): $1\lambda \times \lambda/2$ = 3" by 1.5" (for one element)

Projector Array: 2 by 2 elements with an electrode arrangement to option a preferred aperture directivity

Thin plate geometry for minimum protrusion into the AUV interior volume

Monolithic structure mounting with prescribed element aperture definition

The NRL projector is resonant at 100 kHz but has been designed to deliver high sound pressure levels without electrical response (impedance magnitude and phase) instabilities. The transducer features the first successful stacking of 1-3 piezocomposite materials. This stacking was accomplished through precision alignment of the individual piezoceramic components. Prior to this development, 1-3 piezocomposite materials have been used in transduction applications such as low frequency hydrophones and high frequency, near-field biomedical electronics. Because of the difficulty in stacking the individual layers, underwater projector use had not been pursued prior to this transducer. However, the fact that the material configuration of the 1-3 piezocomposite results in a wide band frequency response void of lateral plate modes, makes this material attractive for wideband transmit application. The objective of the NRL development was to exploit the wideband response and use transducer design techniques to enhance acoustic output.

The design concept of the NRL projector is to operate below the thickness resonance frequency of the 1-3 piezocomposite material. Since a single layer of 0.25-inch thick 1-3 piezocomposite material has a thickness resonance of approximately 200 kHz, NRL chose to mechanically stack two layers together such that the total thickness resonance is half. This means that the upper operating frequency should be 100 kHz. A key to this approach is to utilize a piezocomposite material structure that will output high acoustic source levels without introduction of spurious modes within the band of 10 kHz to 100 kHz. The performance cost for this type of operation is in the peak source level, however, through design means an acceptable output level can be achieved.

An assembly drawing of the NRL projector is shown in figure 2 where there are two layers of 1-3 piezocomposite plates stacked mechanically in series and electrically in parallel with the positive electrodes in the center. This mechanical stacking technique results in decreasing the thickness resonance frequency from 200 kHz to 100 kHz, where 100 kHz is the dictating upper frequency limit of the transducer. The parallel electrical arrangement provides several benefits; an acoustic output increase by a factor of 2 because the layers are half the input electrical impedance because the two layers act as two capacitors in parallel. This output correlates to a +6 dB increase in the source level over that of a single 1-3 piezocomposite plate. Wiring of the two piezocomposite plates in electrical parallel with the positive electrode placed in the center is beneficial because it decreases typical stray capacitance losses between the positive electrode and the natural ground of the water medium. This reduction of stray capacitance helps maintain low EMI noise radiation because the two outer electrodes are designed as the electrical ground planes. This factor becomes important when considering other system components because it means that there is no electrical and magnetic stray noise radiation. The electrodes of the 1-3 piezocomposite were electroplated copper followed by a thin gold covering for corrosion protection.

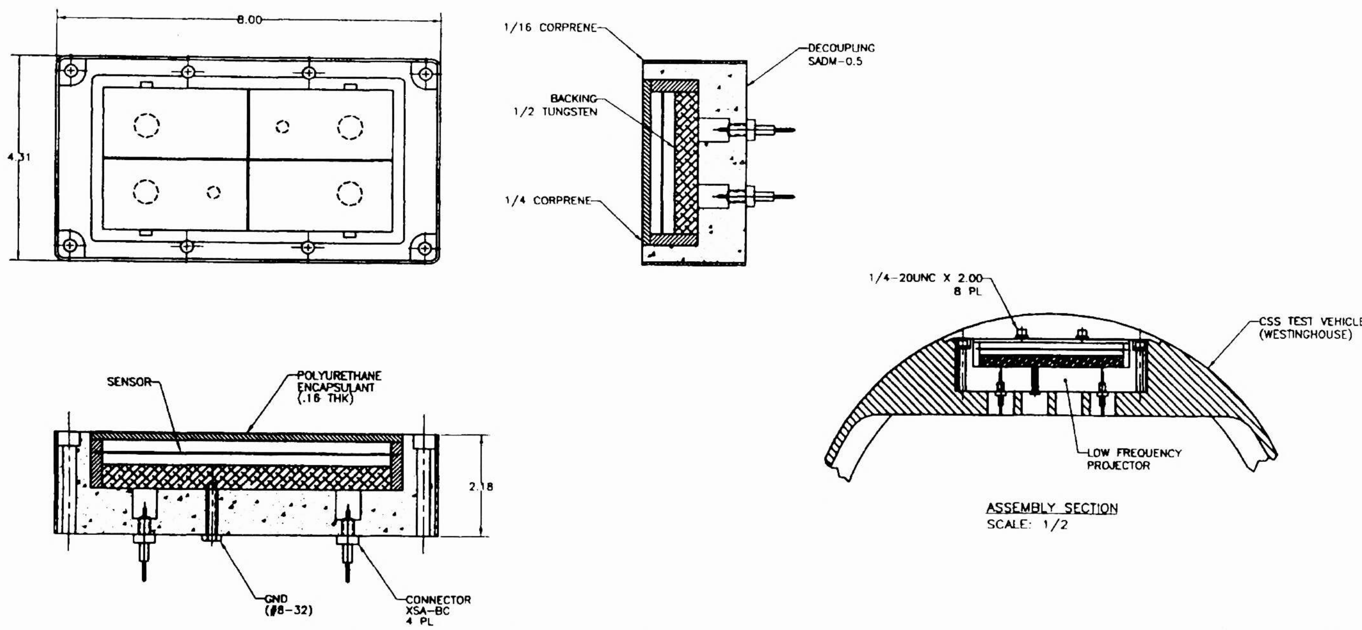

Figure 2: Assembly drawing of the NRL projector.

Although the concept of mechanically stacking is not unique to transducer design, prior to this transducer, the 1-3 piezocomposite material had not been successfully stacked to realize the performance gains. Past efforts have resulted in transducers operating with performances showing resonance frequency behavior of each individual layer thickness mode. When this happens, the transducer will likewise not demonstrate a doubling of acoustic output. To actually realize the benefit of multistacking with 1-3 piezocomposite materials it is necessary to assure that the individual piezoceramic rods of both layers are properly stacked on top of each other as opposed to aligning the individual piezoceramic rods on top of the softer host matrix material. If the individual rods of each layer are not aligned to lay perfectly on top of each other, the transducer will be pushing and pulling on itself.

The assembly drawing of figure 2 also shows a 0.5-inch thick tungsten backing plate which is included in the transducer composition in order to form an acoustic hard boundary condition behind the active layers. For a perfectly rigid backing condition, a theoretical acoustic gain of 6 dB should be added to the source level when compared to an acoustic soft boundary condition such as air. Figure 3 shows an analytical plot of the influence of the thickness of a tungsten backing plate as computed using a 1-D wave propagation model[4] where the model suggest that the 0.5-inch thick tungsten backing layer should provide a +5 dB gain. Because the overall weight of the projector was NOT an issue since it is already necessary to add lead into the MR/H AUV, NRL decided to use the 0.5-inch tungsten backing approach. It should be noted that if weight was of concern, then the model showed that a 0.25-inch thick tungsten backing will still provide greater than a +4 dB gain. Figure 3 shows the predicted source level gain as functions of the backing material thickness and its influence on acoustic source gain over the operating frequency band. The +5-dB source level gain for the 0.5-inch thick tungsten plate is indicative of a 90% forward efficiency of the sound energy. Tungsten was the only candidate backing material that provided these levels of acoustic gain over the operating band within suitable and usable thicknesses in terms of packaging.

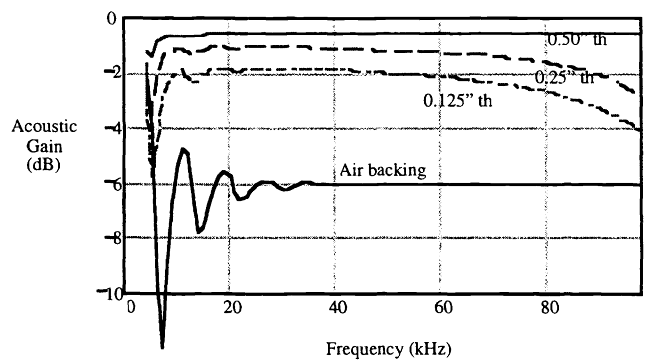

Figure 3: Analytical prediction of acoustic source level gain as a function of tungsten backing plate thickness.

The frame shown in figure 2 is an acoustic decoupling material consisting of lead-loaded silicon polymer particles placed into a syntactic foam host matrix. This material was chosen because it can be machined to a preferred shape while maintain high acoustic decoupling. The presence of the lead loaded particles introduces a high damping component such that acoustic excitation into the MR/H structure should be minimized. Measurements on the decoupling material have shown an insertion loss level of 8 dB/inch at 10 kHz to 26 dB/inch at 20 kHz up to 40+ dB/inch at 100 kHz. These levels of insertion loss help ensure high mechanical and acoustical isolation between the projector and the AUV structure.

The edges of the 1-3 piezocomposite active layers had 0.25-inch corprene strips placed along side where corprene is a cork board type of gasket material that behaves as an acoustic soft boundary. This results in a pressure release condition that is used to absorb lateral acoustic pressures for enhancement of the directivity responses to appear as a baffled rectangular piston.

To ensure that the electrical connections can withstand a high voltage drive level, four separate positive connectors were used with the tungsten backing plate positioned as an electrical ground. Each element aperture has its own connector (Brantner SEA-CON XSA waterproof connector) which may be addressed through rear connections. This concept ensures that there will be no voltage or dielectric cable breakdown between the active tuning step-up transformer and the individual element aperture. It also ensures that there is no radiating EMI (or crosstalk) coupling within the connectors that might interfere with other system components. The location of the connectors was selected to fit within the existing tonpilz holes on the MR/H AUV such that the NRL projector will be a direct plug-in replacement for the existing tonpilz transducers.

III. RESULTS

During each of the fabrication steps, electrical immitance (impedance, admittance,and phases) measurements were conducted to ensure that the expected multistacking performance was being realized. This in-air data was first conducted during procurement of the original plates, then through bonding of the plates into the layered configuration, followed by attachment of the backing plate to the finished transducer. Figure 4 is the admittance plot for each 1λ x λ/2 aperture as measured for the complete (including encapsulation) NRL projector where the thickness resonance frequency is evident at 98 kHz for each element. The responses of each of the apertures is well behaved and in close agreement in terms of both magnitude and frequency response. Also note that there is no apparent resonance frequency behavior at the individual layer frequency of 196 kHz which is a direct indication that the individual rods in the 1-3 piezocomposite layers have been well aligned on top of each other such that characteristics of the single layer are not present. A mode is present in the 30 kHz region. This mode was first noted when the backing mass was attached onto the piezocomposite sandwich because it is related to the quarter wavelength distance of the sandwich and backing plate.

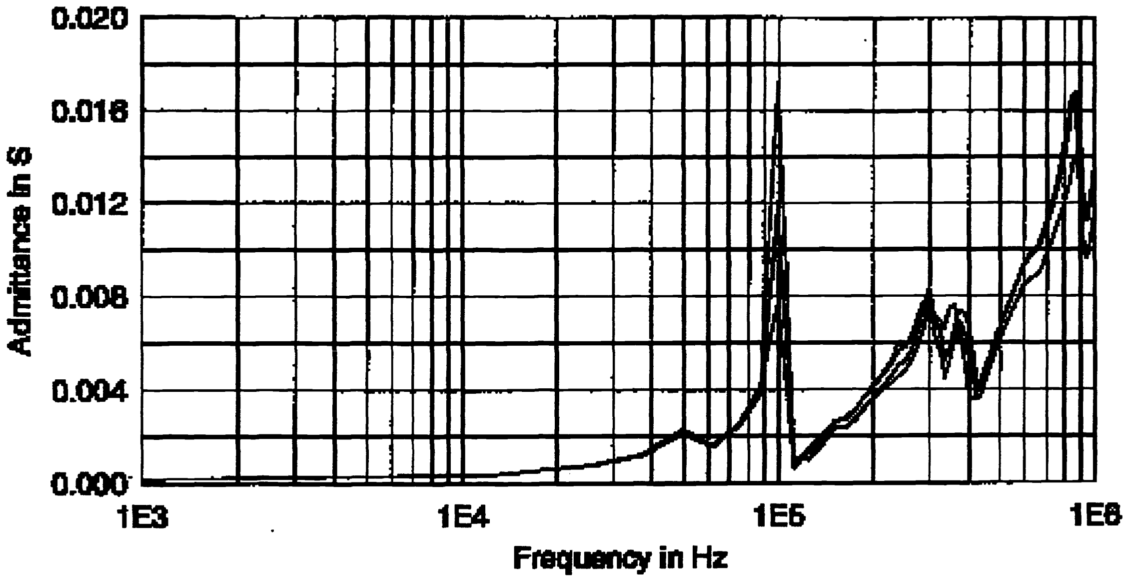

Figure 4: Measured in-air electrical admittance magnitude response of each aperture element.

The NRL projector was acoustically calibrated in-water at the Navy's Underwater Sound Reference Detachment (USRD) Lake Gem Mary facility in Orlando, FL, in August 1996. A plot of the measured transmitting voltage response (TVR) is shown in figure 5 where the TVR is the response normalized for a 1 Volt drive, where the source level (SL) can be computed by adding onto the TVR response[5]. For a drive voltage of 2,000 V_{rms}, the SL will be 66 dB higher than the TVR. This means that the response at 10 kHz is expected to be 192 dB and then rise to 207 dB at 20 kHz.

As with the admittance plot of figure 4, the TVR similarly shows the 30 kHz mode as well as the 100 kHz thickness resonance as well as a lateral resonance at 7 kHz. The presence of the 30 kHz backing plate actually causes an increase in acoustic output in the lower frequency regions by approximately 6 dB. This is also true of the 7 kHz lateral mode which suggests that this projector should be operational down to 5 or 6 kHz.

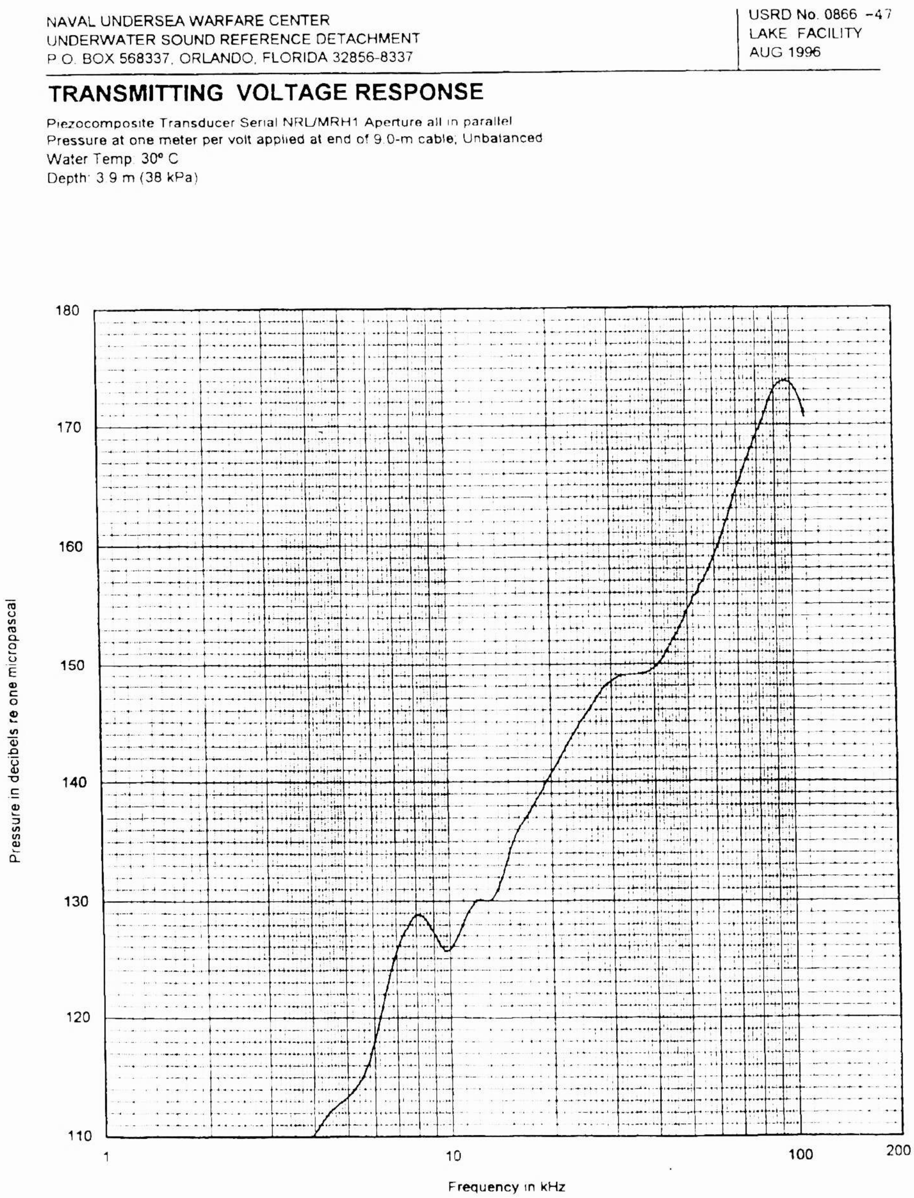

Figure 5: Measured in-water free-field transmitting voltage response.

Along with the measured TVR, transmit directivity patterns were conducted in both planes at 10 kHz, 20 kHz, 50 kHz, and 100 kHz for each aperture as well as for all four apertures in parallel. Table II lists the vertical (XZ-plane) and horizontal (XY-plane) -3 dB down point beamwidths of each aperture, the full aperture and the current MR/H tonpilz projector. The theoretical full aperture is the computed value for a baffled rectangular piston.

TABLE II
Measured Beamwidths (-3 dB) at 20 kHz

Aperture #	Vertical	Horizontal
Theoretical single	50	100
1	61	90
2	49	99
3	49	94
4	41	98
Tonpilz element	59	--
Theoretical Full	24	50
NRL Full	21	51
Tonpilz Full	27	51

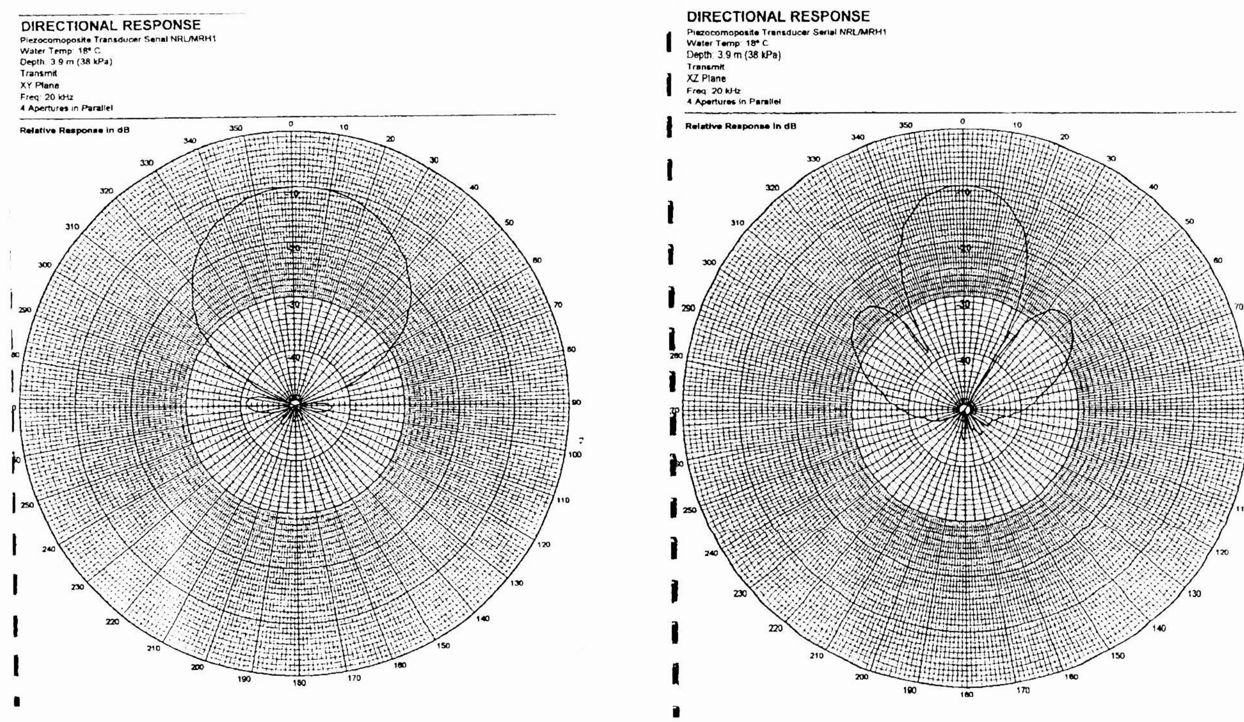

Figure 6: Measured 20 kHz transmit directivity responses for the horizontal (left) and vertical (right) planes.

Figure 6 shows the full aperture beam patterns at 20 kHz for both the horizontal and vertical planes where these responses are representative of the directivity responses at other frequencies in which excellent symmetry and beam profile were realized. The full aperture, in particular, is within the system requirements but the single apertures show some variation, although they are still within specifications. The behavior of all the patterns improve to text book quality as frequency is increased.

IV. BROADBAND TRANSFORMER/FILTER

To accomplish the constant source level of figure 1, a prototype broadband passive transformer/filter was designed and fabricated. The filter has a power amplifier input and a -40 dBV output monitor with an output impedance of 1 kΩ. The transformer is the same one as presently used with the tonpilz transducers in the current MR/H system.

A benchtop study of driving the NRL projector with the broadband transformer/filter was conducted at NRL. An Instrument, Inc. L6 power amplifier with a 5.6 Ω output impedance was used as the benchtop input driver. Attenuated output was measured using an Hewlett Packard 3326A frequency analyzer. Figure 7 shows the measured plot the transformer gain vs. frequency (DC to 100 kHz) while driving the projector. The absolute values should be ignored in this plot because identical attenuators were placed between the input and output of the transformer/filter, however, the relative differences between the input and output are correct. As shown, the transformer voltage gain is 16.4 dB at 9 kHz instead of the desired 20 dB. The gain of the transformer can be increased using a new transformer that has an increased winding ratio of 1.5. Additionally, a useful byproduct of increasing the windings is that an increase in the leakage inductance, stray capacitance and effective load capacitance will provide additional filtering over the 50 kHz to 100 kHz band although the extent of this additional filtering is difficult to define.

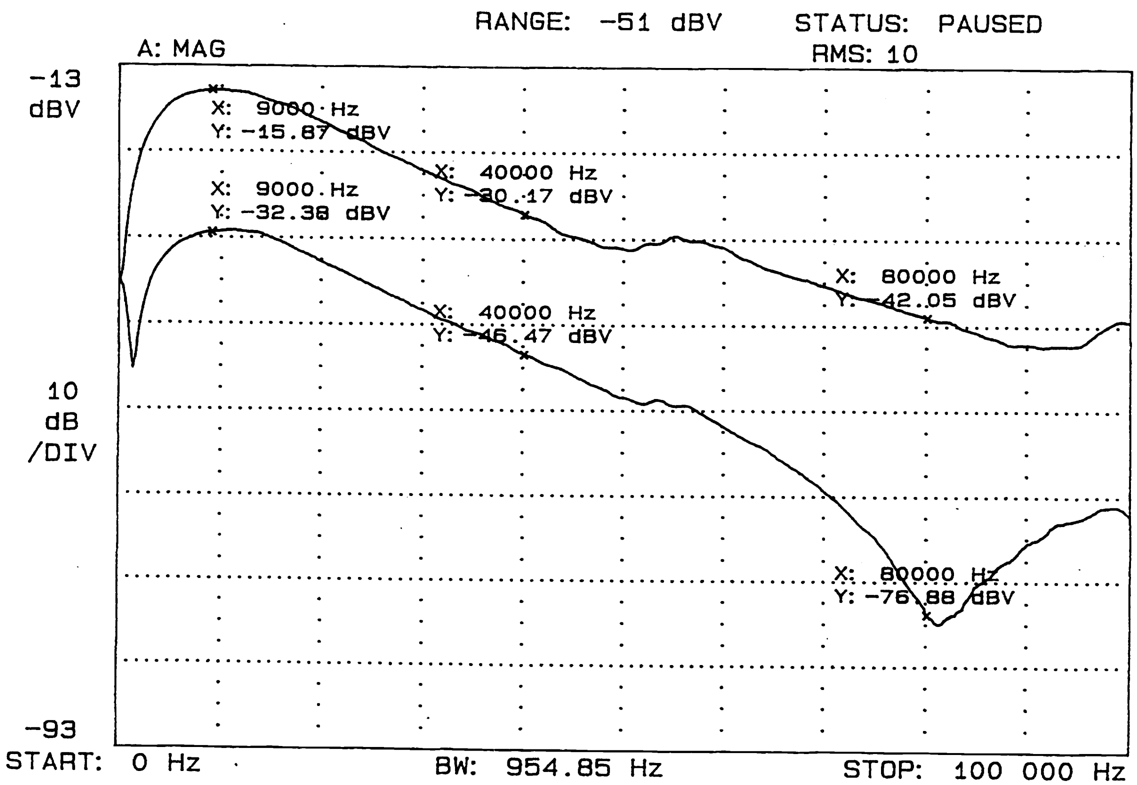

Figure 7: Benchtop measurement of the gain of the broadband transformer/filter over the operating band of interest.

CONCLUSION

An NRL broadband projector concept has been designed, fabricated and tested for application on the MR/H minehunting AUV. The design of the projector contains several advanced features that had not ever been realized before, including the multistacking of 1-3 piezocomposite materials. Measured calibration responses suggest that the projector will accomplish the MR/H system needs as presented Table I. A prototype broadband transformer/filter has recently been fabricated and benchtested. Evaluations of the broadband transformer/filter and NRL projector with the MR/H drive system is scheduled for the near future.

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