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RECENT TRANSDUCTION DEVELOPMENTS IN CANADA AND THE UNITED STATES

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1. INTRODUCTION

Research in the field of high-power low-frequency sonar transducers over the last fifteen years has been sustained by advances in submarine noise reduction and the promise of long range detection at low frequencies [1-3]. With the emergence of new high-power transduction materials and the rapid evolution of fast computers and powerful modelling techniques, this field has been fertile ground for transduction innovation [4, 5]. Some of these innovations have occurred at the Defence Research Establishment Atlantic (DREA) in Canada and at the Naval Undersea Warfare Center (NUWC) in the United States. Through partnerships with industry and universities, our laboratories have been involved in the development of a number of high-power commercial transducers to meet naval needs [6, 7].

Specifically, high-power transducer developments at DREA and NUWC include performance improvements to conventional piezoelectric ceramic projectors, progress in the exploitation of magnetostrictive and electrostrictive driver materials in sonar projectors, and advances in transduction design techniques. While high power, low frequency, wide bandwidth, and high efficiency remain the primary performance objectives behind these developments, low weight and small size are desirable physical attributes that require equal attention by the designer.

This paper presents some of the key performance parameters of many types of projectors and emphasizes the importance of various new active materials. Although measured values of the parameters will be reported wherever possible, in some cases estimates are given and duly noted. A table that summarizes the performance parameters is included in an appendix for convenience. Since it is not possible to cover each projector in detail in the limited space available here, brief descriptions of selected projector designs will be given. Finally, we encourage the interested reader to obtain copies of the references cited for more complete performance data such as plots of electrical admittance, transmitting voltage or current response, and directivity patterns.

2. FLEXTENSIONAL PROJECTORS

2.1 Flextensional Transducer Operation and Classification

One of the most extensively studied type of transducer for high-power low-frequency sonar applications is the flextensional projector. In a generic sense, flextensional transduction can be described as electrically-stimulated mechanical amplification. A specific example is the flexural excitation of a curved shell by an internal ferroelectric ceramic stack that, through the converse piezoelectric effect, is forced into extensional-compressional vibration by an applied electric field. Since the shell is contiguous to the acoustic medium, sound is radiated at wavelengths that are much larger than the dimensions of the transducer itself. Consequently, when operated at frequencies near its fundamental flexural mode, the flextensional transducer is omnidirectional. Further discussions concerning the operation and performance capabilities of flextensional transducers are given by Marshall et al. [8] and Oswin and Dunn [9].

In 1969, flextensional transducers were grouped into five classes by Brigham and Royster [10, 11] in order to simplify the identification of a growing number of flextensional designs at that time. Recently, their classification scheme was extended by Rynne [5] to include two additional classes. The criteria that distinguish the classes are based on specific performance enhancements and the shapes of the shells. The Class I transducers consist of eccentric convex shells that have rotational symmetry about their long central symmetry axes. Class II transducers have Class I shells but extended driving mechanisms for greater power capability. Class III transducers feature at least two contiguous Class I shells, each shell exhibiting its own flexural resonance frequency. If the resonances are in close proximity to each other, they can be combined to give large operating bandwidths. Class IV transducers are characterized by eccentric convex shells that have constant cross-sections when viewed along central orthogonal axes. Class V transducers have eccentric convex shells with rotational symmetries about their short symmetry axes. Classes VI and VII are the same as Classes V and IV respectively, but with concave shells.

2.2 Class I Flextensional Projectors

The barrel-stave flextensional projector has been extensively studied at DREA for almost a decade and a number of versions have been built, tested, and used on a regular basis in sea trials. The technology was patented by McMahon and Jones [12] and transferred to Sparton of Canada Limited in the early 1990s. This projector can be considered a Class I flextensional transducer with a concave (rather than convex) set of staves. A typical DREA piezoceramic barrel-stave flextensional projector is shown on the left in Figure 1, and is also shown on the left in Figures 2 to 4 for comparative purposes. The driver consists of ten axially-poled lead zirconate titanate ceramic rings assembled into a stack and connected in parallel electrically. A steel end plate with an octagonal cross-section is bonded to each end of the stack. Eight concave aluminum staves, each with a radius of curvature of 20 cm, are bonded and screwed to the steel end plates. Narrow slots, about 1 mm in width, separate adjacent staves. An aluminum end cap is bonded to the outside surfaces of the end plates and supports four stainless steel stress rods that prestress the stack. Since the staves are concave, hydrostatic pressure enhances the prestress. A neoprene rubber boot is stretched over the projector in order to prevent the ingress of seawater through the slots.

A Sparton Model 03BA1100 barrel-stave projector, which is based on the typical DREA barrel-stave design shown on the left in Figure 1, was calibrated in 14.6 m (48 ft) of seawater at the DREA acoustic calibration facility on Bedford Basin, and the following performance parameters were reported by Jones [13]. The resonance frequency (f_r) was 1100 Hz, the transmitting voltage response (TVR) at resonance was 122.3 dB//1 μPa-m/V, the mechanical quality factor (Q_m) was 5.2, and the electroacoustic efficiency (η) at resonance was 74%. If driven with an electric field of 3.9 kVrms/cm (10 Vrms/mil), the source level (SL) would be 194.1 dB//1μPa-m. Since the projector mass is 2 kg, the maximum outside diameter is 80 mm, and the length is 150 mm, then the mass figure of merit (FOM_m) and volume figure of merit (FOM_v), as defined in Eqs. (A1) and (A2) of the Appendix, are 19 W/kg-kHz-Q and 50 W/m^3-Hz-Q respectively. These parameters are listed in Table A1 of the Appendix.

A lightweight barrel-stave projector, shown on the right hand side of Figure 1, was designed at DREA for air-launched and neutrally-buoyant sonar applications by modifying three key features of the typical projector shown on the left hand side of Figure 1. The steel end plates were replaced with aluminum plates, the staves were reduced in thickness, and the stave radius of curvature was reduced from 20 cm to 14.6 cm, i.e. the curvature of the staves was increased. All three of these modifications reduced the mass of the projector [14]. By using a combination of finite element analysis and experimental measurement, it was possible to offset the reduction in effective coupling coefficient due to bending of the more compliant aluminum plates, by decreasing the radius of curvature of the staves to 14.6 cm. At the same time, the increase in resonance frequency due to this change in radius of curvature was opposed by frequency decreases due to thinner staves and compliant end plates. A projector, with a mass of 1.5 kg, was produced with reasonable acoustic performance parameters. In 14.6 m (48 ft) of seawater, the resonance frequency was 1450 Hz, the TVR at resonance was 122.6 dB//1µPa-m/V, the quality factor was 4.1, and the efficiency at resonance was 50%. The predicted source level at resonance is 194.4 dB//1µPa-m using an applied field of 3.9 kVrms/cm (10 Vrms/mil). The figures of merit are 26 W/kg-kHz-Q and 63 W/m^3-Hz-Q, slightly better than the Sparton barrel-stave projector (see Table A1). More details on this projector are given by Jones and Reithmeier [15] and Jones and Lewis [16].

In the late 1980s, the electroacoustic efficiencies of DREA piezoceramic-driven barrel-stave flextensional projectors fell in the range of 50 to 70%. By the early 1990s, design improvements and tighter manufacturing tolerances used in the Sparton commercial barrel-stave projectors extended this range to 75%. Recently, this efficiency range was increased to 80% by lowering the slot-width-to-stave-width ratio and consequently, reducing the losses associated with the interaction effects between the boot and the slots. This ratio was reduced by doubling the overall size of the barrel-stave projector without changing the 1 mm slot width [17]. The large DREA barrel-stave projector is shown on the right side of Figure 2. Since it had been observed that the performance parameters of barrel-stave projectors vary with water depth and drive voltage, one of these large projectors was calibrated at the NUWC Seneca Lake sonar test facility at Dresden NY, to quantify these observations. The water depth at Seneca Lake, being much greater than that available at the DREA calibration facility, was advantageous for this work, which was done as a joint DREA-NUWC research venture. The results were presented at the 125th Meeting of the Acoustical Society of America by Jones and Moffett [18]. As an example of the results, in 61 m (200 ft) of water, the projector resonated at 790 Hz with a mechanical quality factor of 3.6 and an efficiency of 81%. When driven with a field of 3.9 kVrms/cm (10 Vrms/mil), the measured source level was 204.3 dB//1µPa-m. The projector has a mass of 16.7 kg. The figures of merit are 47 W/kg-kHz-Q and 162 W/m^3-Hz-Q, which are the best values for a DREA piezoceramic barrel-stave flextensional projector to date (cf. the other DREA barrel-stave projectors in Table A1).

The performance parameters of two barrel-stave flextensional projectors were reported by Moffett and Clay [19]. The first was a piezoceramic Edo 6993 barrel-stave projector which has a mass of 4.1 kg and was calibrated in 9 m of water. The resonance frequency was 1560 Hz, the quality factor was 3.0, and the efficiency was 50%. The source level, measured in a pressure vessel, was 194.7 dB//1µPa-m when the transducer was subjected to a field of 3.9 kVrms/cm (10 Vrms/mil). The figures of merit are 14 W/kg-kHz-Q and 49 W/m^3-Hz-Q. The second was a NUWC barrel-stave projector driven with magnetostrictive Terfenol-D rods that were biased using neodymium-iron-boron permanent magnets. This projector has a mass of 5.1 kg and was calibrated at a depth of 61 m (200 ft). At a resonance frequency of 1480 Hz, the mechanical quality factor and overall efficiency were 3.8 and 15% respectively. The measured source level of 202.9 dB//1µPa-m was limited by the strength of the stave-end plate interface. The figures of merit for this barrel-stave projector are 60 W/kg-kHz-Q and 267 W/m^3-Hz-Q.

Finally, a magnetostrictive barrel-stave projector driven by Terfenol-D has been built and tested by C. Purcell at DREA. Cobalt-samarium permanent magnets provided the bias field, and ferrite disks and a cylindrical scroll fabricated from Metglas 2605TCA ribbons comprised the flux return path. The projector has a mass of 3.9 kg and was calibrated at a depth of 18.3 m (60 ft). The resonance frequency was 1060 Hz, the quality factor was 3.4, the measured source level at resonance was 197.7 dB//1 µPa-m, and the overall efficiency was 32%. The source level is believed to be limited by saturation in the magnetic circuit [20]. The figures of merit for this barrel-stave projector are 35 W/kg-kHz-Q and 93 W/m^3-Hz-Q.

2.3 Class II Flextensional Projectors

One way to increase the power output of the Class I piezoceramic barrel-stave flextensional projector without altering the resonance frequency, increasing the maximum driving field, or changing the driving material, is to add more volume of ceramic to the driver. This is easily accomplished for the barrel-stave projector by employing the Class II flextensional design concept described by Royster [11] and Rolt [21]. Thus, an extended-stack projector was built at DREA and is shown on the right in Figure 3. The length of the ceramic stack was doubled to increase the power capability, and the main radiating surface consisting of eight staves was left unaltered so that the change in resonance frequency was minimized. The steel end plates were replaced by cylindrical steel housings in order to accommodate the twenty ring ceramic stack.

The performance parameters were measured by Jones et al. [22] in 30 m of seawater at the DREA acoustic calibration facility. The resonance frequency was 1270 Hz, the mechanical quality factor was 4.3, and the electroacoustic efficiency was 64%. A source level of 196.1dB//1 µPa-m was measured using an applied field of 3.9 kVrms/cm (10 Vrms/mil). The mass of the projector is 3.9 kg. The figures of merit are 16 W/kg-kHz-Q and 49 W/m^3-Hz-Q.

2.4 Class III Flextensional Projectors

Resonant transducers with low mechanical quality factors can be difficult to design when frequency and size constraints are imposed upon the transducer designer. One solution is to use the Class III design concept where two closely coupled resonance modes are combined to achieve broad bandwidth [11, 21]. A Class III dual-shell barrel-stave flextensional projector, shown on the right in Figure 4, was built and tested at DREA to investigate the extent to which the quality factor could be lowered. Two stacks, consisting of six piezoceramic rings and one machinable glass ceramic ring each, were mounted on either side of a steel center plate having an octagonal cross-section. A steel end plate, also with an octagonal cross-section, was bonded to the free end of each stack, and two sets of eight aluminum staves were attached to the end and center plates. Since one set of staves was 4 mm longer than the other, the longer set resonated at a lower frequency than the shorter set and the two modes combined in-water to give a low overall quality factor. The results of this study have been reported by Jones and Lewis [23].

This projector has a mass of 3.1 kg and was calibrated in 14.6 m (48 ft) of seawater at DREA. A single peak in the TVR was observed. The frequency at the peak was 1720 Hz, the Q_m was 3.0, the predicted source level with an applied field of 3.9 kVrms/cm (10 Vrms/mil) was 190.8 dB//1 µPa-m, and the efficiency was 73%. By replacing the neoprene boot with a stiff and perhaps lossier butyl boot, the frequency of the peak increased to 1800 Hz and the mechanical quality factor decreased to 2.2. The reduction in quality factor was likely a result of the frequency increase due to the added stiffness of the butyl boot, however, a decrease in the mechanoacoustic efficiency associated with possible higher losses in the butyl boot would also contribute to lower mechanical Q. A further reduction in quality factor was achieved by mounting the unbooted projector on a tracer lathe and machining the long staves down in thickness. As the staves got thinner they became more compliant and the resonance frequency associated with the long staves was reduced [24]. In this way the modes were separated and the overall bandwidth in water increased. Thus, at 1650 Hz, the Q_m was 1.8 and the predicted source level at 3.9 kVrms/cm (10 Vrms/mil) was 189.4 dB//1 µPa-m. The figures of merit are 8 W/kg-kHz-Q and 24 W/m^3-Hz-Q. Another dual-shell barrel-stave projector, currently under construction at DREA, has been designed for higher source level, lower frequency, and low mechanical Q, and should give better figures of merit.

2.5 Class IV Flextensional Projectors

Being the most popular and exploited of the genre, Class IV flextensional transducers are those which are identified by those outside the transducer community as 'flextensional transducers'. This class of flextensional has been developed extensively, with prototypes designed and fabricated for operation over a frequency range spanning from very low frequency to almost 10 kHz. This flextensional is the epitome of Woollett's characterization of a 'miniature' transducer [25, 26]. Figure 5 is a cutaway of a section of a Raytheon 1 kHz Class IV flextensional and depicts a design typical of this class of flextensional transducer. Lockheed Sanders has been the most prolific manufacturer of this class of flextensional and their Model 30 transducer, which resonates at 1030 Hz and delivers 207.5 dB//1 µPa-m of source level, is the industry standard with more than 110 units manufactured and delivered to various customers. The mass and volume figures of merit for the Model 30 are 25 W/kg-kHz-Q and 61 W/m^3-Hz-Q respectively, and represent typical values for the class. The Allied Signal Model DX776 and British Aerospace (now BAeSEMA) Model WA316 have been produced in array quantities and both of these 800 Hz transducers are configured like the Sanders Model 30 with aluminum shells. Alternate shell materials like fiberglass have been used in flextensionals such as the 400 Hz Sanders Model 40 as a means to lower the resonance frequency of the transducer while maintaining bandwidth and compact size.

Recent US efforts have revolved around increasing the power output of these transducers by replacing the PZT drive stacks with electrostrictive ceramic such as lead magnesium niobate (PMN). For the specific design case in which the flextensional is electric field-limited and not stress-limited in the drive stack or shell, a 6 dB gain in source level is expected from this material upgrade. The Allied Signal DX835 flextensional was built as both PZT and PMN prototypes and the PMN version achieved a 3.6 dB advantage over the PZT version before becoming cavitation-limited at the 91.4 m (300 ft) test depth (see Table A1). Testing of the transducer at a cavitation free depth would result in more than 5 dB source level gain. For this specific transducer, the figure of merit for mass will increase from 30 (for the PZT) to 155 (for the PMN at full power), a five-fold advantage for PMN.

A problem which may occur with this class of flextensional (and for that matter, most of the classes) is that if the symmetry of the acoustic field around the transducer is disrupted, this may excite asymmetric modes of the shell and driver. Thus, placing a flextensional transducer with a specific geometry a certain distance from a baffle or other transducer may at a specific frequency excite a spurious mode in the transducer. Jack Butler has turned this 'problem' around and conceived a transducer [27, 28] which utilizes the asymmetric excitation of the shell to produce a unidirectional radiator. In a paper being given at this conference [29], Butler et al. provide recent developments and test results with a 3.5 kHz prototype and summarize the concept and mode of operation in detail. Figure 6 is a cutaway of a 900 Hz directional flextensional currently under development. The TR-1426 is being designed and fabricated by Massa Products under a NUWC Small Business Innovation Research (SBIR) contract and is the next step in the evolution of this idea. The contract will culminate during late summer 1995 with a 5 element vertical line array test at the NUWC Seneca Lake deep-water test facility. The development is designed to demonstrate the ability to build a high power directional transducer which will permit a single vertical line array to transmit left/right. Predictions indicate that the individual transducer will develop at least 213 dB//1μPa-m of directional mode source level at resonance with a mechanical Q_m less than 7 and operate reliably at 152.4 m (500 ft) depth. The radiated beam pattern front-to-back ratio over the operating band defined by the Q_m will vary from 20 to 40 dB when using complex phasing.

2.6 Class V Flextensional Projectors

DREA began to build and test Class V ring-shell flextensional projectors in the late 1970s. Some of these experimental projector designs are described in a review paper by McMahon [30]. The active component of a ring-shell projector consists of a ring made from piezoceramic plates and steel wedges. Compressive prestress is applied to the ring using fiberglass roving and epoxy. Two convex metal shells are attached to the ring and are driven into flexure when an electric field is applied to the ceramic. This technology was transferred to Sparton of Canada in 1982 and today they market a variety of ring-shell projectors that resonate at frequencies below 3 kHz, and can be fitted with passive depth compensation systems [31].

For comparative purposes, the in-water performance parameters of the Sparton Model 34SA0400 ring-shell projector, as measured in 15.2 m (50 ft) of seawater at the DREA acoustic calibration facility, are presented here. The projector itself is shown in Figure 7. At its resonance frequency of 400 Hz, the projector had a mechanical quality factor of 3.5 and an electroacoustic efficiency of 83%. The predicted source level using a field of 3.9 kVrms/cm (10 Vrms/mil) is 213.2 dB//1μPa-m. The mass is 225 kg and the mass and volume figures of merit are 55 W/kg-kHz-Q and 81 W/m^3-Hz-Q respectively.

2.7 Class VI Flextensional Projectors

The first DREA Class VI ring-shell flextensional projector was built in the mid 1970s [30, 32]. This projector consisted of a ceramic ring driver and two concave aluminum shells. At a resonance frequency of 600 Hz, the measured source level and efficiency exceeded 201 dB//1μPa-m and 80% respectively. By the late 1970s DREA was studying mainly Class V ring-shell projectors and it wasn't until 1988 that DREA and Sparton of Canada returned to the Class VI concept in an effort to design a shock resistant ring-shell projector [33]. Thus, a Class VI ring-shell projector (with concave shells) was made from a standard Sparton Class V projector (with convex shells) by installing the shells upside down (see Figure 8). The prototype projector, designated Sparton Model 18SI0700, was calibrated in 30 m of water at the Seneca Lake test facility. The resonance frequency was 700 Hz, the quality factor was 3.9, and the efficiency was 90%. If driven with a field of 3.9 kVrms/cm (10 Vrms/mil), the predicted source level would be 205.2 dB//1μPa-m. The projector has a mass of 43 kg and the mass and volume figures of merit are 25 W/kg-kHz-Q and 71 W/m^3-Hz-Q respectively.

2.8 Class VII Flextensional Projectors

In 1966 Howard Merchant, who was working at Honeywell at the time, was granted a flextensional transducer patent [34] which included a sketch of a peanut-shell-shaped flextensional. This Class VII flextensional, essentially a concave Class IV oval flextensional, apparently was never reduced-to-practice until last year. The NUWC magnetostrictive barrel-stave projector development [19] identified many design and engineering problem areas of which two were stress failures encountered at the stave/end mass interface (i.e., the stave shears off) and difficulties in the design of a good magnetic return path for the magnetostrictive driver. Lockheed Sanders became involved in the design effort and what eventually became obvious was the idea that if one eliminated the joint between the barrel stave and the end mass by going to a continuous assembly and further discarded the circular symmetry of the barrel stave so that two Terfenol-D drivers in parallel can be used to simplify the magnetic circuit, one has designed a Class VII flextensional transducer. The basic Merchant design appears to suffer from a low coupling coefficient and this required design improvements and innovation to eliminate the deficiency. As a result of this evolution, two Class VII flextensionals were designed and built by Lockheed Sanders with Terfenol-D magnetostrictive drivers.

Figure 9 pictures the two transducers built. The smaller of the transducers was designed for operation around 900 Hz and has a uniform wall thickness shell and Terfenol-D rods which are biased with DC imposed via the coils. The larger of the two transducers was designed for 500 Hz operation and utilizes a tapered shell and permanent magnet bias. The bias is achieved with neodymium-boron-iron magnets interspersed in the Terfenol-D drive rods. Figure 10 is a photo of the interior of the permanent magnet transducer. A significant advantage of a Class VII flextensional (over that of a Class IV) is that the imposition of hydrostatic pressure on the shell results in an increase in prestress on the driver. This is the exact opposite of the Class IV oval case, which must have a very stiff shell and has to be preloaded such that as the transducer is exposed to hydrostatic pressure (which subtracts out the preload), there is still sufficient preload in the shell at depth to prestress the driver and prevent it from going into tension during AC drive. Thus the Class VII (along with Classes I, II, III, & VI presented in this paper) has the advantage that initial high prestress is not required. This minimizes potential creep in both the shell and driver material over the life of the transducer.

Unburdened from the requirement to statically prestress the driver, the designer is able to design a more compliant shell and better match it to the compliance of the driver. By combining this advantage with the low modulus of Terfenol-D, a transducer can be designed which maximizes coupling coefficient and bandwidth. Although a PZT or PMN driven Class VII flextensional will offer good performance and long-term advantage due to low static stress, the mating of the compliant Class VII shell with Terfenol-D results in a remarkable transducer. The DC-biased version of this transducer achieved a source level of 212 dB//1 μPa-m at 930 Hz in a package the size of a lunch pail. The mass figure of merit measured was 210 W/kg-kHz-Q and the volume figure of merit was 710 W/m^3-Hz-Q. The permanent magnet biased version achieved a source level of 211.8 dB//1 μPa-m at 490 Hz before the drive pulse length/duty cycle combination inadvertently heated the drivers to the point that the rare earth magnets started to demagnetize. This resulted in degraded performance and a mass figure of merit of only 113 W/kg-kHz-Q. It was reassuring that this transducer development demonstrated the ability to take a material energy density improvement and actually incorporate it into a device and retain the performance advantage. Table 1 (see Section 6) indicates a 9.3 dB advantage of Terfenol-D over PZT-8 whereas the DC-biased Class VII prototype has an 8.5 dB edge over a Model 30 ceramic flextensional.

3. FREE-FLOODED RINGS

Piezoceramic free-flooded ring projectors were used by DREA in the 1960s to investigate deep sea propagation paths. The rings consisted of carefully-aligned ceramic plates and metal wedges and were compressively biased with fiberglass roving and epoxy. The rings were isolated from the seawater environment with oil-filled boots. At least two design features made them attractive for the DREA deep water work. First of all, the projectors did not require a pressure release mechanism, which allowed them to operate over an extensive range of depths with little change in performance. Second, the transducer could be designed to achieve a wideband frequency response by decreasing the height to diameter ratio of the ring until the cavity resonance frequency associated with the enclosed water column was increased towards, and closely coupled to the ring resonance frequency [35]. This free-flooded ring technology was transferred to Sparton of Canada Limited by 1990, and prototype rings were delivered to DREA as part of that technology transfer contract to support low frequency active research. These transducers are capable of radiating more than 35 kW of acoustic power over a bandwidth exceeding 1 kHz and have been shown to perform at depths greater than 4500 meters.

The latest Sparton ring design, Model 28FC1000 shown in Figure 11, has a diameter of 0.72 m, a height of 0.30 m, and a mass of 270 kg. Its performance parameters were obtained in 123.4 m (405 ft) of water at Seneca Lake in 1994 [36]. The measured response curve was characterized by a low frequency peak at 960 Hz, a second peak at 1600 Hz, a flat region between the two peaks, and a relatively rapid roll-off above 2000 Hz. Since the TVR values remained above 148 dB//1µPa-m/V over the entire frequency range from 850 to 2000 Hz, plenty of power is available throughout this band. The measured source level at the 1600 Hz peak was 217.7 dB//1 µPa-m and was limited by cable and amplifier ratings. Thus, the driving field of 2.07 kVrms/cm (5.3 Vrms/mil) associated with this source level fell short of the rated driving field of 2.5 kVrms/cm (6.4 Vrms/mil) recommended by Sparton. The mechanical Q at 1600 Hz was 1.4, which highlights the broadband nature of this projector. The mass and volume figures of merit, at the 2.07 kVrms/cm drive level, are 43 W/kg-kHz-Q and 96 W/m^3-Hz-Q respectively. If the projector was driven at the rated driving field (6.4 Vrms/mil), the mass and volume figures of merit would be expected to increase to 64 W/kg-kHz-Q and 141 W/m^3-Hz-Q.

4. HYBRID LONGITUDINAL VIBRATORS

A magnetostrictive/piezoelectric hybrid tonpilz transducer was patented in 1984 by Butler and Clark [37]. This transducer was called a hybrid because of its synthesis of piezoelectric and magnetostrictive drive materials, resulting in unique properties. The primary design is that of a double-ended tonpilz which takes advantage of both the inherent 90° phase difference between the magnetostrictive and piezoelectric velocities for the same driving voltages and an additional 90° phase shift due to time delays associated with the compressional wave speed within the transducer. The exact details of the device and how it works can be found in Reference [38].

NUWC interest in the device resulted in a Small Business Innovation Research (SBIR) contract which culminated in the design, fabrication, and test of a 12 element, close-packed planar array of hybrid transducers with a 4.5 kHz resonance frequency. The configuration of the prototype design of the double-ended tonpilz can be seen in Figure 12. The transducer is mechanically unidirectional in the free-field and acoustically directional when driven in an array which minimizes diffraction. Test results indicated a 15 dB front-to-back pressure ratio when driven in the array [39]. A secondary advantage of the transducer is that it is self-tuning. Additionally, as a result of the electrical and magnetic energy shared at the electrical resonance of the hybrid transducer, the coupling coefficient is enhanced by a factor as great as $\sqrt{2}$ which can be a 41% increase.

After the twelve element bi-directional array was built and tested, the development moved on to designing a unidirectional tonpilz. It then became evident that by manipulation of the masses within the assembly, the bandwidth of the transducer could be greatly enhanced. Figure 13 depicts the bandwidth gain that can be achieved by this optimization. Referring to the figure, it can be seen that the original hybrid has a bandwidth of 40%, whereas the bandwidth of the enhanced hybrid has exceeded 100%. Based on these predictions, it can be asserted that a typical piezoelectric ceramic tonpilz, in a closely-packed array with an external tuning inductance, could be replaced by a hybrid which greatly increases the bandwidth, has built-in tuning, and exhibits an optimized coupling coefficient.

5. COPOLYMER PROJECTORS

Polyvinylidene fluoride (PVF_2) and its copolymer with trifluoroethylene (PVF_2EF_3) have been traditionally used in hydrophone construction with recognized success. The materials have not been seriously considered as projector materials because of several rather obvious material properties which are incompatible with underwater high power projector engineering requirements. The electric fields required to produce the maximum strain in the materials are 75 times that of ceramic which makes for a formidable engineering challenge. An additional problem to address is the dielectric loss which is higher than that of piezoelectric ceramic. A third problem area is the low coupling factor of the material. Despite these shortcomings, piezopolymers have some positive qualities. They are more closely matched in mechanical impedance to sea water than their ceramic counterparts and as a result can operate over broader bandwidths. The low mechanical impedance of the polymer proves to be of additional merit in that its mismatch to a metal backing plate is sufficient to preclude the need for an acoustic pressure release.

The adaptation of the material to practical transducer designs can take several directions. Design efforts at NUWC have been spearheaded by George Kavarnos and focus on the concept of a transparent half-wave projector. An initial design [40] consisted of 7 layers of ~200 µm copolymer one inch square, which started as powder, then was solvent cast, annealed, electroded, poled, and consolidated. The completed projector resonated at 542 kHz with a mechanical Q of 2.3, a transmitting voltage response of 156 dB//1µPa-m/V, and an electroacoustic efficiency of 12%. Dino Roberti at Raytheon Co. has taken a slightly different tack and is concentrating on developing quarter-wave resonators which can be used in closely packed planar arrays. Roberti's R&D copolymer prototype has a quarter-wave resonance of 14.6 kHz and has achieved a source level of 214 dB//1µPa-m with a significant bandwidth indicated by a mechanical Q of 2.4. Figure 14 shows the transducer before installation in its waterproof housing. This source level resulted from a drive level of 375 Vrms/mil with the eventual goal being to drive the material at 500 Vrms/mil. The mass and volume figures of merit of this prototype, at the 375 Vrms/mil drive level, are 80 W/kg-kHz-Q and 331 W/m^3-Hz-Q respectively. These figures of merit exceed those which can be obtained from standard, high power tonpilz (longitudinal vibrator) transducers which, at high power, require mechanical prestress and other complications. What remains to be defined are the practical limits to this copolymer transducer and to what frequencies it can be designed.

Table 1. High power projector materials.

Material	Field Limit (rms)	Young's Modulus Y (GPa)	Strain (0-pk) (ppm)	Energy Density 1/2 Y S^2 (J/m^3)	Relative dB
PZT-8	10 V/mil	74	125	578	0
PMN	10 V/mil	71	445	7030	10.9
PMN	20 V/mil	71	891	28183	16.9
PVDF (voided)	750 V/mil	0.9	1020	468	-9.2
P(VDF-TrFE)	750 V/mil	3	1023	1570	3.4
Terfenol-D	64 kA/m	29	580	4878	9.3
Terfenol-D	175 kA/m	59	810	19355	15.3
TbDy	22 kA/m	25	1980	49005	19.3

6. HIGH POWER PROJECTOR MATERIALS

High power projector materials have traditionally focused on the lead zirconate titanate compositions known as PZT-4 and PZT-8. With the exception of a few barium titanate holdouts, all production underwater projectors in use in the U.S. Navy are of one of these two compositions. Recent trends have been to develop and introduce new high energy density drive materials into the Fleet and to tailor each material to its specific need or application. New drive materials include Terfenol-D [41-43], low temperature magnetostrictive materials [44], lead magnesium niobate (PMN) [45], and piezoelectric polymers [40]. Each of these materials has a potential use or niche and each has advantages and disadvantages. A useful way to rank these materials among themselves and to the PZT benchmark, is to calculate the field-limited energy density of the basic material. This metric is defined as one-half the product of the Young's modulus of the material times the square of the maximum strain obtainable at the electric or magnetic field limit of the material. This permits a comparison of materials on a per unit volume basis. Table 1 is a summary of materials currently of interest. The field limit used for the PZT-8 benchmark was 10 V/mil which is the industry standard for reliability and acceptable losses. Lead magnesium niobate (PMN) is an electrostrictive ceramic which promises high strain while all of its other properties (notably cost) resemble that of PZT. The values given for PMN are representative of its current state of development. The energy density of polyvinylidene fluoride (PVDF) voided homopolymer is considerably less than that of PZT but its ρc makes for a very broadband device. Its copolymer, poly(vinylidene fluoride-trifluoroethylene) is also suited for broadband operation but is stiffer and at its full field limit becomes a true competitor to PZT if one can conquer the engineering challenge of reliably applying the field of 750 V/mil. The drive levels associated with the Terfenol-D tabulation are for the general case of limiting harmonic distortion to approximately 15% to permit broadband transducer operation and for the higher drive case in which it is presumed that operation will only be around resonance where the projector will act as a bandpass filter and suppress radiated harmonics. Terbium-dysprosium, used at cryogenic temperatures, yields the highest known magnetostriction of any material. The material cited is $Tb_{0.6}Dy_{0.4}$ at 77 K and represents data collected at a relatively low magnetic field.

7. CONCLUSIONS

The performance parameters of the projectors presented in this paper are testimony to the growing belief that magnetostrictive Terfenol-D and electrostrictive PMN are transducer materials that are well suited to low-frequency high-power sonar systems. Not only are the high power capabilities being realized, but the often quoted problem of low efficiency is being addressed, for example, the efficiency values reported for three transducers driven with Terfenol-D and PMN (see Table A1) are approximately 45%. Future material and transduction engineering advances may push this figure significantly over the 50% mark.

The goal of any high power projector is to be operating at its mechanical and electrical limits and be almost cavitating. Reference [41] presents the argument of the optimum mechanical Q of a transducer working at its limits and shows that each driver material has an optimum power output which is defined as the peak intersection of the mechanical and electrical stress limits of the transducer as a function of Q_m. What was shown in the reference was that for a transducer in an array whose loading was such that the transducer Q_m would be about 2, Terfenol-D was the material of choice since the power peak was in that range of Q. If the transducer then operates at its cavitation threshold, one has achieved optimal performance.

The importance of using concave shells in flextensional projector designs should also be emphasized. Five classes of flextensional projectors presented in this paper have such a shell configuration. The advantages include a more compact design, opportunities to better match the shell and driver compliances, and the elimination of high prestress levels, which can present the manufacturer with a somewhat dangerous assembly step and can cause damage to the transducer over its lifetime.

For some sonar applications, self-supporting flextensional projectors suffer from depth limitations, and various techniques are currently being investigated at DREA to improve this situation for the barrel-stave projectors. However, the high power capability of Terfenol-D and PMN may present the transducer designer with new ways to trade off power with depth capability in applications that do not require the full power improvement offered by these materials.

8. ACKNOWLEDGMENTS

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10. APPENDIX

The performance parameters presented in this paper are summarized in Table A1. The full source level unit specification is dB//1μPa-m. The overall efficiencies η include the losses associated with the DC bias requirements of magnetostrictive projectors that do not use permanent magnets. The projector mass figure of merit is given by

$$\mathrm{FOM_m} = \frac{\text{radiated power}}{\text{mass} \times \text{frequency} \times \text{quality factor}}, \qquad \text{(A1)}$$

where the radiated power is given in watts, the projector mass is given in kilograms, the frequency is the in-water resonance frequency in kilohertz, and the mechanical quality factor is determined at the -3 dB points on the TVR plot, or by using the half-conductance frequencies on the in-water electrical conductance curve. The projector volume figure of merit is given by

$$\mathrm{FOM_v} = \frac{\text{radiated power}}{\text{volume} \times \text{frequency} \times \text{quality factor}}, \qquad \text{(A2)}$$

where the volume in m^3 is estimated from the projector dimensions and the resonance frequency is given in hertz. The volumes for the flextensional transducers represent overall outline dimensions required for placement in an array and thus are greater than the actual volume. The entries in Table A1 are ordered by frequency.

Table A1. Performance summary of various sonar projectors.

Projector ID	f_r (Hz)	Q_m	SL (dB)	η (%)	Mass (kg)	FOM_m (W/kg-kHz-Q)	FOM_v (W/m^3-Hz-Q)
Sparton PZT Ring-Shell Model 34SA0400 Class V	400	3.5	213.2	83	225	55	81
Sanders Terfenol-D[a] Model 70 "dogbone" Class VII	490	4.5	211.8	45	54	113	250
Sparton PZT Ring-Shell Model 18SI0700 Class VI	700	3.9	205.2	90	43	25	71
DREA PZT Barrel-Stave large Class I	790	3.6	204.3	81	16.7	47	162
NUWC/Sanders Terfenol-D Model 8 "dogbone" Class VII	930	4.7	212.0	46	15.4	210	710
Sanders Model 30 PZT Class IV	1030	4.5	207.5	80	43	25	61
DREA Barrel-Stave[b] Terfenol-D Class I	1060	3.4	197.7	32	3.9	35	93
Sparton PZT Barrel-Stave Model 03BA1100 Class I	1100	5.2	194.1	74	2.0	19	50
DREA PZT Barrel-Stave high power Class II	1270	4.3	196.1	64	3.9	16	49
DREA PZT Barrel-Stave lightweight Class I	1450	4.1	194.4	50	1.5	26	63
NUWC Barrel-Stave[c] Terfenol-D Class I	1480	3.8	202.9	15	5.1	60	267
Edo PZT Barrel-Stave Model 6993 Class I	1560	3.0	194.7	50	4.1	14	49
Sparton Free-Flooded Ring[d] PZT Model 28FC1000	1600	1.4	217.7	57	270	43	96
DREA PZT Barrel-Stave broadband dual-shell Class III	1650	1.8	189.4	50	3.1	8	24
Allied Signal DX835E[e] PMN Class IV	2500	4.6	210.2	43	10	83	185
Allied Signal DX835 PZT Class IV	2500	5.7	206.6	>90	9.5	30	64
Raytheon copolymer projector	14600	2.4	214.0	26	1.0	80	331

[a]Limited by internal heating problem.

[b]Limited by saturation in the magnetic circuit.

[c]Limited by stave attachment method.

[d]Limited by cable and amplifier ratings.

[e]Limited by cavitation and electrical difficulties.

Figure 1. Typical (left) and lightweight (right) Class I barrel-stave flextensional projectors.

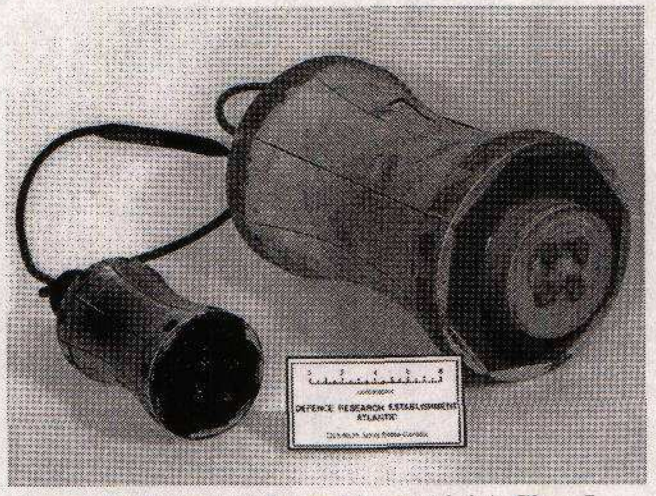

Figure 2. Typical (left) and large (right) Class I barrel-stave flextensional projectors.

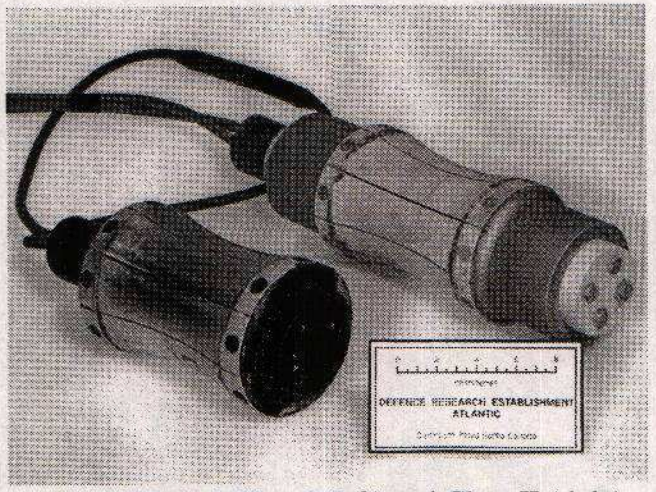

Figure 3. Typical Class I (left) and Class II (right) barrel-stave flextensional projectors.

Figure 4. Typical Class I (left) and Class III (right) barrel-stave flextensional projectors.

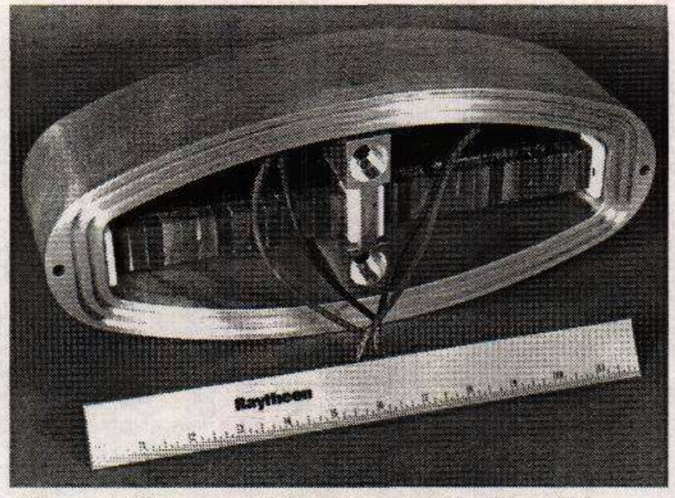

Figure 5. Cutaway of Raytheon 1 kHz Class IV flextensional transducer. Photo courtesy of Raytheon Company.

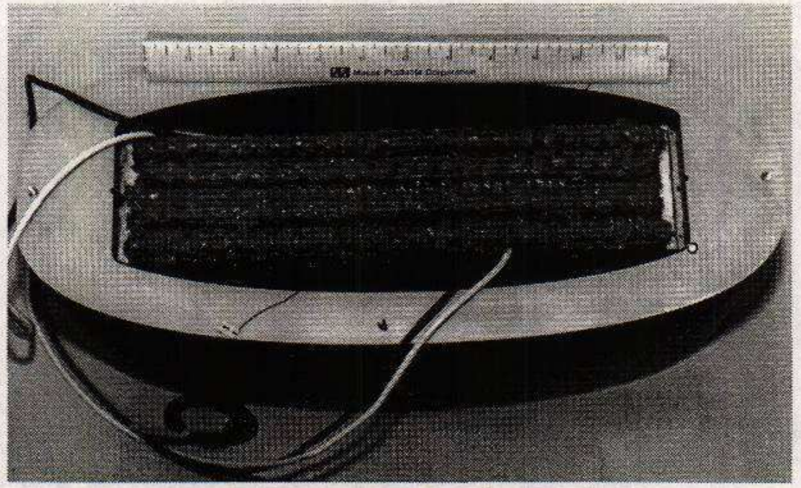

Figure 6. Cutaway of Massa 900 Hz Class IV directional flextensional. Photo courtesy of Massa Products.

Figure 7. Class V ring-shell flextensional projector. Photo courtesy of Sparton of Canada Limited.

Figure 8. Class VI ring-shell flextensional projector. Photo courtesy of Sparton of Canada Limited.

Figure 9. Lockheed Sanders 930 Hz (left) and 490 Hz (right) Class VII flextensionals.

Figure 11. Free-flooded ring projector. Photo courtesy of Sparton of Canada Limited.

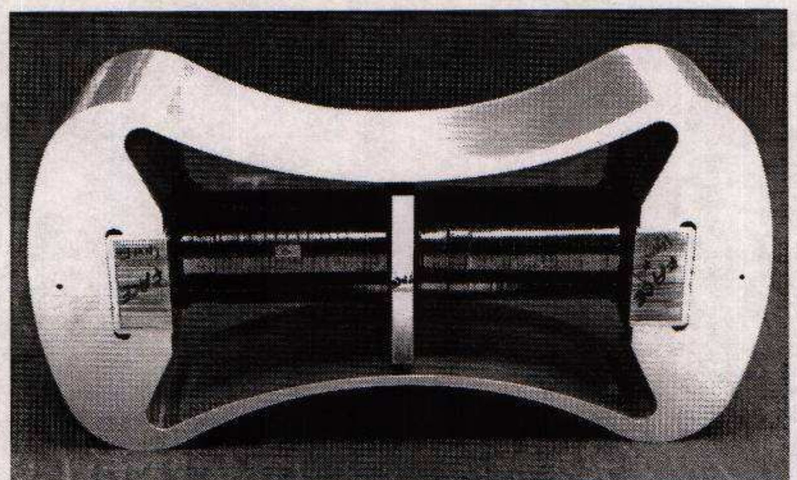

Figure 10. Cutaway of section of Lockheed Sanders permanent magnet biased, Terfenol-D Class VII tapered shell flextensional. Photo courtesy of Lockheed Sanders.

Figure 12. Massa hybrid transducer.

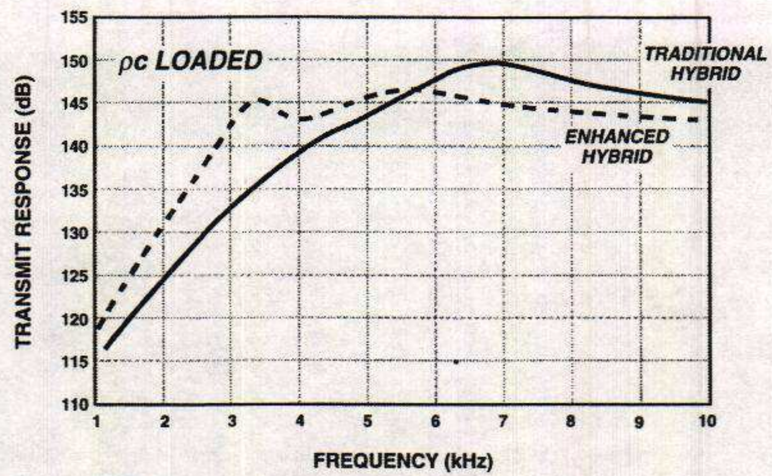

Figure 13. Transmit response curves for array-loaded traditional hybrid transducer (solid) and enhanced hybrid transducer (dashed).

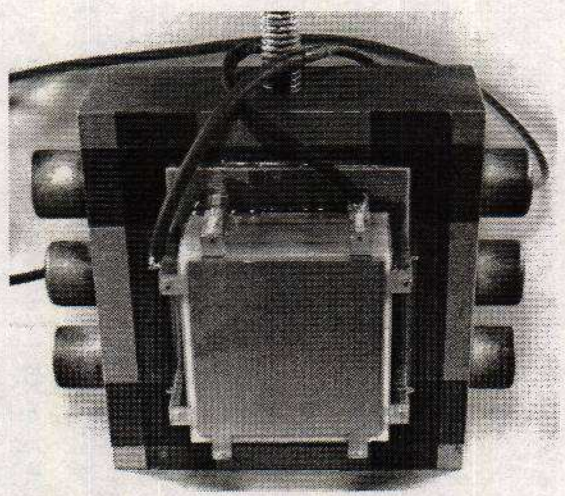

Figure 14. Raytheon copolymer projector prototype mounted on test backing plate. Photo courtesy of Raytheon Company.