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TITLE

BARREL-STAVE FLEXTENSIONAL TRANSDUCERS FOR SONAR APPLICATIONS

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BARREL-STAVE FLEXTENSIONAL TRANSDUCERS FOR SONAR APPLICATIONS

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ABSTRACT

Barrel-stave flextensional transducers are low frequency underwater projectors that can be used as active components in long-range sonar systems or as versatile sound sources in oceanographic applications. The advantages offered by this type of flextensional transducer include low frequency, high power, small size, low weight, post-assembly frequency tuning, and low cost due to simplicity in its design and assembly. The construction of three barrel-stave projectors, investigated at the Defence Research Establishment Atlantic (DREA) in recent years, is briefly described. The performance goals for each of these projectors are shown to be consistent with the criteria that distinguish the first three classes in the Brigham-Royster classification scheme for flextensional transducers. Important in-water performance parameters, such as the resonance frequencies, transmitting voltage responses, source levels, mechanical quality factors, and electroacoustic efficiencies, are presented. In addition, these parameters are compared to those of other experimental and commercial barrel-stave flextensional designs.

INTRODUCTION

The flextensional transducer concept has been known to researchers involved in the design of acoustic transducers for more than sixty years. The mechanics of this type of transducer were meticulously described by Hayes (1936) in a patent that disclosed the first flextensional transducers, which were expressly designed for audible sound generation in aeroacoustic applications. By using the analogy of mechanical leverage, Hayes showed that the flextensional principle involved the conversion of small longitudinal displacements of a magnetostrictive driver into relatively large flexural displacements of a surrounding shell. Since the shell was in contact with the radiating medium, sound was generated efficiently, at frequencies considerably lower than longitudinal mode transducers of similar size.

In the 1940s and 1950s, when the relationship between low frequency sound and long range sound propagation in the ocean became better understood, and when piezoelectric ceramics with high coupling factors became available, the first flextensional transducers for low-frequency high-power underwater sonar systems were built. A number of flextensional configurations were devised by the pioneering efforts of researchers like Abbott (1959), Toulis (1966), and Merchant (1966). Three historical papers covering the evolution of sonar and the development of flextensional transducers were written by Klein (1968), Hueter (1972), and Rolt (1990) and are highly recommended for the interested reader. Today, the flextensional transducer is one of the most actively studied underwater projectors for sonar and oceanographic applications. Further discussions on these applications are found in the papers by Decarpigny et al. (1991) and Boucher (1993).

In order to facilitate discussion of the various types of flextensional transducers, Brigham and Royster (1969) proposed a classification scheme that consisted of five classes distinguished by specific performance enhancements and shell morphologies. Photographs showing transducers belonging to each flextensional class can be found in the papers by Royster (1970) and Rolt (1990). The Brigham-Royster classification scheme was extended to seven classes by Rynne (1993), in a paper that included discussion of a number of key flextensional transducer patents.

In this paper, we focus on the performance of three classes of one particular transducer design, the barrel-stave flextensional projector. This projector was patented by McMahon and Jones (1990) and has been in use at the Defence Research Establishment Atlantic (DREA) since the late 1980s.

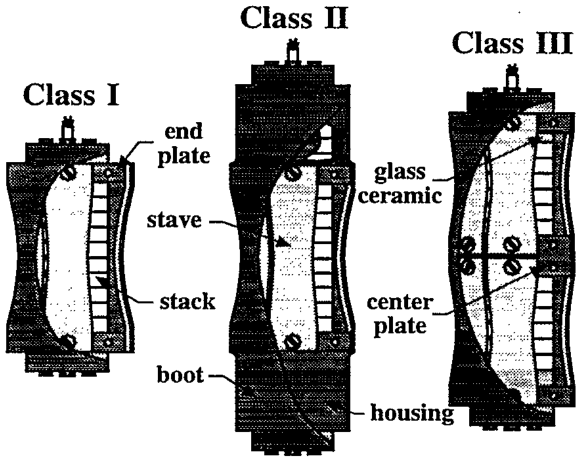

Figure 1. Three barrel-stave flextensional projector classes.

CONSTRUCTION

Cutaway views of three barrel-stave flextensional projectors are shown in Figure 1. On the left side of the figure is a Class I barrel-stave projector. This projector was designed at DREA using analysis tools like electroelastic finite elements and lumped-parameter equivalent circuits. When the first experimental projectors were constructed and tested, a number of geometric configurations and material selection issues were investigated empirically to validate the theories and to establish a set of design procedures for performance optimization. From this multi-faceted research approach, a DREA design, optimized for operation at a resonance frequency of 1100 Hz, was transfered to Sparton of Canada Limited through a technology transfer contract in the early 1990s and is commercially available today as Sparton Model 03BA1100. This projector is being used by many companies and research institutions around the world for various underwater applications.

The Sparton Class I projector consists of a stack of ten lead zirconate titanate piezoceramic rings bonded together and connected in parallel electrically. Bonded to each end of the stack is a carbon steel end plate that has an octagonal cross-section. Eight concave aluminum staves are screwed and bonded to the eight sides of the end plates. When the stack is electrically excited into longitudinal vibration, the staves are driven into flexure. To minimize the risk of mechanical failure, the stack is prestressed by stainless steel stress rods to ensure that it remains in compression when operating in shallow water or when undergoing test procedures in air. At greater water depths, hydrostatic pressure adds to this prestress due to the concave profile of the staves, allowing safe operation of the projector up to its rated drive voltage. A neoprene 5109-S rubber boot is stretched over the staves to prevent water ingress through the gaps left between adjacent staves. The length of the projector is 15 cm, the maximum outside diameter is 8.1 cm, and the mass is 2.0 kg.

A Class II barrel-stave projector is shown in the center of Figure 1. The main characteristic of this flextensional class is that the ceramic driver extends beyond the extremities of the radiating staves. In this way, the power handling capability of the transducer is increased due to the greater volume of ceramic allowed in the stack. This power enhancement can be achieved without appreciably changing the projector resonance frequency, since the resonance is primarily determined by the material properties and physical dimensions of the staves. In the case of the DREA Class II barrel-stave projector, the stack is extended to twice the length (i.e. twenty rings instead of ten) by using cylindrical steel housings with octagonal bases, instead of flat plates. The ceramic stack in the Class II projector of Figure 1 can be seen through a cutaway hole in the upper housing. A 5109-S rubber boot is used to maintain the air backing of the staves. The length and diameter of the experimental DREA Class II projector are 23 cm and 8.5 cm respectively. The mass of the projector is 3.9 kg.

Finally, a Class III dual-shell barrel-stave flextensional projector is shown on the right hand side of Figure 1. This projector is a doubly-resonant design that is capable of achieving a broadband response in water. It is this broadband capability that distinguishes this flextensional class from the others. An experimental Class III projector was built at DREA to investigate the bandwidth parameter.

The dual-shell projector consists of a steel center plate bonded to two stacks. Each stack consists of six piezoceramic rings and one machinable glass-ceramic ring. The glass-ceramic ring at the top of the upper stack is 4 mm shorter than the other glass-ceramic ring at the bottom of the lower stack. Hence, the upper stack will resonate at a higher frequency than the lower stack. A steel end plate is bonded to the glass-ceramic rings. The end and center plates have octagonal cross-sections so that sixteen concave aluminum staves can be affixed. Like the stack lengths, the eight staves surrounding the upper stack are 4 mm shorter than the eight staves surrounding the long stack. Since all sixteen staves on the Class III projector are shorter than the staves on the Class I and II projectors, the center frequency of the former is higher than the resonance frequencies for the latter two projectors. A 5109-S rubber boot is stretched over the staves to keep water from filling the interior of the projector. The overall length of the Class III projector is 19 cm, the maximum outside diameter is 8.2 cm, and the mass is 3.1 kg.

LOW-LEVEL MEASUREMENTS

The low drive level performance parameters for the Sparton Class I, DREA Class II, and DREA Class III barrel-stave flextensional projectors discussed in the previous section, were determined from measurements made at a depth of 14.6 m in seawater at the DREA calibration facility on Bedford Basin. The drive levels did not exceed 100 Vrms for any of these measurements. Standard calibration techniques, such as those described by Bobber (1970), are employed at this facility.

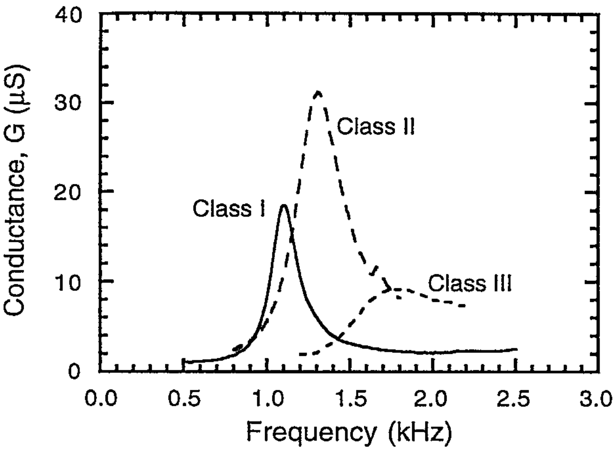

Figure 2. Electrical conductance curves for the three barrel-stave projectors.

Figure 2 shows the electrical conductance (G) for the three projectors. The peaks, corresponding to the resonance frequencies, are located at 1100, 1300, and 1720 Hz for the Class I, II, and III projectors respectively. The corresponding conductance values at the peaks are 18.5, 31.3, and 9.2 μS.

The transmitting voltage responses (TVR) for the three projectors are plotted in Figure 3. The TVR values at the resonance frequencies given above are 122.3, 123.8, and 119.0 dB//1μPa-m/V, again, for the Class I, II, and III projectors respectively.

The directivity patterns at the resonance frequencies of the three projectors were measured in the vertical (XZ) and horizontal (XY) planes. All of the patterns in both planes are essentially omnidirectional. This was to be expected since the projectors are small compared to the wavelengths of the sound that they radiate at resonance, and hence, they behave as monopole radiators to a first approximation. An example

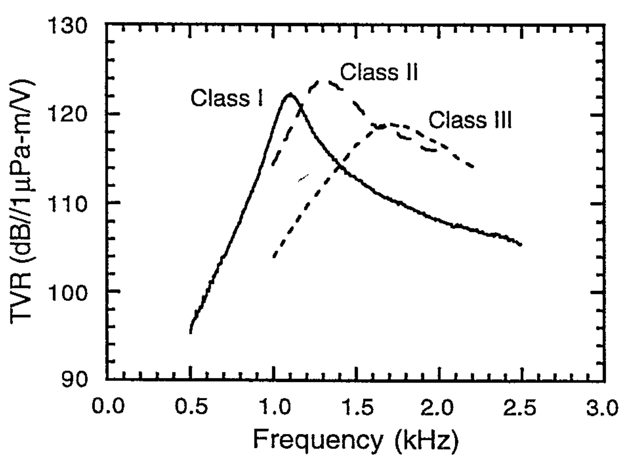

Figure 3. TVR curves for the three barrel-stave projectors.

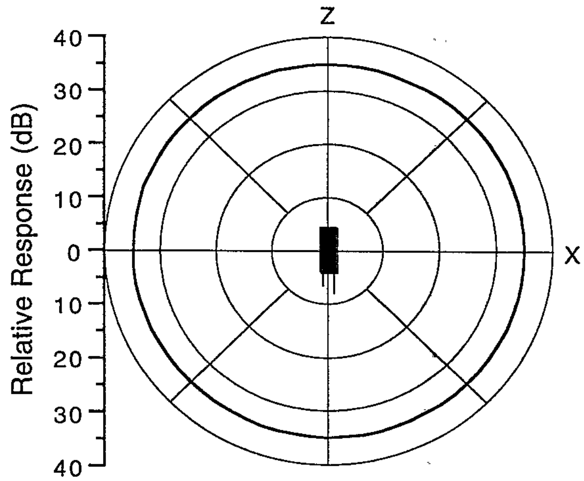

Figure 4. Directivity pattern in the vertical (XZ) plane for the Class II projector operating at 1300 Hz.

is given in Figure 4 for the vertical (XZ) plane of the DREA Class II projector at its 1300 Hz resonance frequency. The directivity index (DI) associated with this pattern is 0.08 dB. This index was determined using the numerical integration techniques described by Bobber (1970). The DI for the Class I projector was 0.14 dB. Since the DI was not calculated for the Class III projector, a value of 0.1 dB, which is close to the average of the indices for the other two projectors, is assumed for the purposes of estimating efficiencies.

Electroacoustic efficiencies (η) for the three barrel-stave projectors can be determined using the following expression;

$$10\log(\eta) = \mathrm{TVR} - 10\log(G) - \mathrm{DI} - 150.8 \ , \qquad (1)$$

where η is given in percentage and the factor 150.8 takes into account the density and sound speed of seawater at the DREA calibration facility. Substituting the resonance values for the TVR, G, and DI determined above, we obtain the following efficiencies for the Class I, II, and III projectors at their resonance frequencies: 74%, 63%, and 70% respectively.

Normally, the bandwidth (Δf) and the mechanical quality factor (Q_m) are determined from the half-conductance points on the curves in Figure 2. However, since the conductance curve for the Class III projector does not drop to the half-conductance point on the high frequency side of the resonance peak due to the influence of higher frequency modes, and since all three projectors are nearly omnidirectional, Δf and Q_m are determined with reasonable confidence from the -3 dB points on the TVR curves in Figure 3. Since the resonance frequencies (f_r) are known, and the -3 dB bandwidths for the Class I, II, and III projectors are 210, 350, and 570 Hz, the corresponding mechanical quality factors, given by

$$Q_m = f_r / \Delta f \ , \qquad (2)$$

are 5.2, 3.7, and 3.0.

Table 1. Summary of the low-level performance parameters for the three barrel-stave projectors.

Parameter	Class I	Class II	Class III
f_r (Hz)	1100	1300	1720
Δf (Hz)	210	350	570
Q_m	5.2	3.7	3.0
G (μS)	18.5	31.3	9.2
TVR (dB)[a]	122.3	123.8	119.0
DI (dB)	0.14	0.08	0.1
η (%)	74	63	70
SL (dB)[b]	194.2	195.7	190.9

[a]Full unit is dB//1μPa-m/V.
[b]Full unit is dB//1μPa-m.

The source levels (SL) at resonance for a given root mean square driving voltage (Vrms) can be estimated from the TVR values using the following expression:

$$SL = TVR + 20\log(Vrms)\ . \tag{3}$$

Thus, if we assume that the maximum operating field for lead zirconate titanate ceramic is 3.94 kVrms/cm (see discussion by Butler et al., 1994), then for the Class I, II, and III projectors that all use 1 cm thick ceramic rings, the predicted source levels are 194.2, 195.7, and 190.9 dB//1μPa-m respectively.

Table 1 summarizes the measured and calculated low-level performance parameters for the three barrel-stave flextensional projectors near their resonance frequencies. Additional information on the construction and performance of the Class I, II, and III projectors can be found in Jones (1993), Jones et al. (1995), and Jones and Lewis (1994).

Note that the predicted source level of the Class II projector is higher than that of the Class I projector (see Table 1). However, part of the reason is that the resonance frequencies are different. Thus, in order to fairly evaluate the effects of the different stack lengths, we account for this frequency difference in the following section.

In addition, although the Class III projector has the broadest bandwidth of the three projectors in Table 1, it is by no means the best that can be obtained with this design. Since quality factors as low as 3 are achievable from some singly-resonant designs, it is instructive to try to reduce this parameter to its minimum value by modifying the design. Therefore, two experimental techniques, described in the Bandwidth Enhancements Section, were used to determine the minimum quality factor of the Class III projector.

HIGH-LEVEL MEASUREMENTS

The 200 Hz difference in the resonance frequencies of the Class I and Class II projectors (see Table 1) is due in part to the stave thicknesses of the two projectors. The Class II projector has staves that are about 1.5 mm thicker than those on the Class I projector. Note that since the outside diameters mentioned in the Construction Section were 8.1 and 8.5 cm, the extra 1 mm difference in outside diameter is due to the difference in the stretched boot thicknesses of the Sparton and DREA boots.

The effect that this 1.5 mm extra stave thickness has on the resonance frequency and TVR of the Class II projector is given by empirical relations found in Jones and Lewis (1995a). In that work it was found that the resonance frequency and TVR increased with stave thickness by 137 Hz/mm and 0.81 dB/mm respectively. The frequency increased with stave thickness due to the associated increase in stave stiffness. The TVR increased with frequency because the transducer behaves like a monopole radiator.

Therefore, if the staves on the Class II projector were machined down (on a tracer lathe for example) by 1.5 mm to match the stave thickness on the Class I projector, the resonance frequency would decrease from 1300 Hz to about 1100 Hz, the same frequency as the Class I projector. This confirms the earlier assertion that the resonance frequency of the Class II design is governed primarily by the properties and geometry of the staves. At the same time however, the TVR would be reduced from 123.8 to 122.6 dB//1μPa-m/V, which is only 0.3 dB better than the TVR of the Class I projector. This marginal increase in acoustic output provides little impetus to adopt the Class II design.

The difficulty with the analysis just given is that the barrel-stave flextensional projector is nonlinear with drive voltage and water depth, and therefore, the low level TVRs may not yield the same results as TVRs obtained at the rated drive levels. These nonlinear effects were investigated by Moffett and Clay (1990) and Jones and Moffett (1993). Their papers indicated that the nonlinearities may be related to boot intrusion into the gaps between the staves. As the depth increases, hydrostatic pressure forces rubber into the gaps causing an increase in hoop stiffness and resonance frequency and a decrease in TVR. As the drive level is increased, the losses associated with boot intrusion into the gaps are less important due to the increased amplitude of vibration at high drive levels. The result is a decrease in resonance frequency and an increase in TVR with drive level. Although the Sparton and DREA boots are made from the same 5109-S neoprene rubber recipe, their properties may be significantly different since the raw rubbers were not formulated by the same manufacturer, the curing procedures were not identical, the boot geometries were different, and the boot installation techniques were different. Therefore, the magnitude of the nonlinearities associated with the two projectors may be different, hence, the true power improvement of the Class II design should be determined at high drive levels.

The high drive level measurements were performed at the DREA acoustic calibration facility in 30 m of seawater. This depth was required in order to avoid cavitation. TVRs for the two projectors were obtained at a number of drive voltages between 1.0 kVrms and 3.5 kVrms. The 3.0 kVrms TVRs

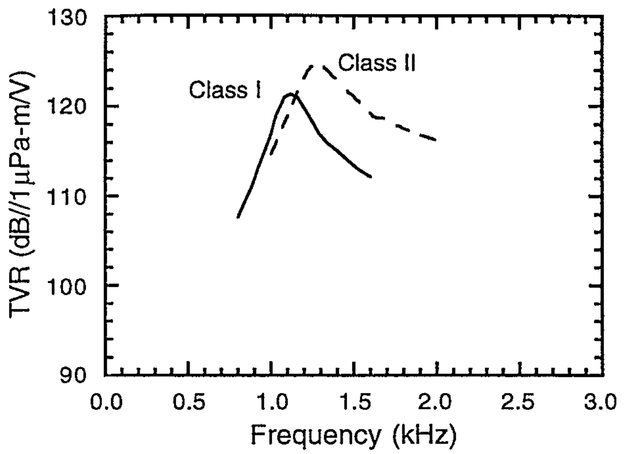

Figure 5. High drive level TVR curves for two barrel-stave projectors obtained at 3.0 kVrms.

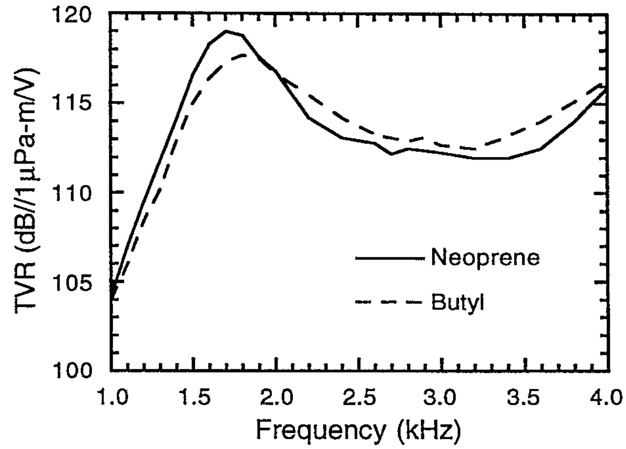

Figure 6. Neoprene 5109-S versus butyl boots.

are shown in Figure 5 for illustrative purposes. Note that the resonance frequencies and TVR values at resonance have shifted due to the change in calibration depth as well as the change in drive voltage (cf. Figure 3). When we visually compare the difference in the resonance TVR values for the two projectors in Figure 3 to that in Figure 5, we notice that the difference is greater in the latter figure. Therefore, it is useful to repeat our comparative analysis of the output of the Class I and II projectors, but this time at the rated field limit of 3.94 kVrms/cm.

The high level resonance frequencies and associated TVR values for both projectors are plotted against drive voltage and fitted with least squares regression lines. Using these fits, the predicted resonance frequencies and TVR values at resonance, for an applied voltage of 3.94 kVrms, are 1110 Hz and 121.8 dB//1μPa-m/V for the Class I projector, and 1260 Hz and 125.2 dB//1μPa-m/V for the Class II projector. Now if we hypothetically machine 1.1 mm of aluminum off the Class II staves, the resonance frequency of this projector would be reduced to that of the Class I projector and its TVR would fall to 124.3 dB//1μPa-m/V, where we have again used the 0.81 dB/mm result. Thus, we have a net TVR improvement of 2.5 dB over that of the Class I projector at the rated drive level and at the same resonance frequency. Hence, the DREA Class II barrel-stave projector is a bona fide high power version of the Sparton Class I projector.

BANDWIDTH ENHANCEMENTS

The -3 dB bandwidth for the DREA Class III barrel-stave projector driven at low levels is given in Table 1 as 570 Hz. This bandwidth can be increased by using a different type of rubber boot and/or by separating the two closely coupled resonance frequencies that are characteristic of this dual-shell design. Both techniques were employed by Jones and Lewis (1994) and the procedures and results are summarized below.

The neoprene 5109-S rubber boot was removed from the Class III projector and replaced with a butyl rubber innertube. The projector was recalibrated at 14.6 m depth at the DREA calibration facility and the TVR is shown in Figure 6 as a dashed line. The TVR for the projector fitted with the neoprene boot is also shown for comparison. From Table 1, the resonance frequency, TVR at resonance, -3 dB bandwidth, and mechanical quality factor for the Class III projector fitted with a neoprene boot were 1720 Hz, 119.0 dB//1μPa-m/V, 570 Hz, and 3.0 respectively. The same parameters for the butyl-booted projector were 1800 Hz, 117.8 dB//1μPa-m/V, 830 Hz, and 2.2. Since the butyl boot was stiffer than the neoprene boot, the resonance frequency increased, however, greater intrinsic losses in the butyl boot may be responsible for the reduction in TVR at resonance. Both of these butyl boot properties act to reduce the mechanical quality factor and increase the bandwidth.

A further increase in bandwidth was realized by separating the two resonance frequencies. Since the longer set of staves resonated at a lower frequency than the shorter set of staves, then by reducing the thickness of the longer staves by machining the staves on a tracer lathe, their resonance frequency was lowered. Since the higher resonance frequency associated with the set of shorter staves was not altered, the two modes separated from each other and the overall bandwidth increased. The maximum thickness of the long staves was reduced from 4.6 mm to 4.1 mm. Another butyl boot was fitted on the projector and it was subsequently recalibrated.

The TVR of the machined Class III projector is shown as the dashed line in Figure 7. The solid line is the unmachined projector. Both TVR curves in the figure were obtained from the Class III projector fitted with butyl boots. Two peaks are now visible in the TVR curve, one at 1650 Hz with a TVR value of 117.4 dB//1μPa-m/V, and one at 2180 Hz with a TVR value of 114.9 dB//1μPa-m/V. These peaks correspond to the individual resonance frequencies of the two sets of staves. With the machined projector and a butyl boot, the

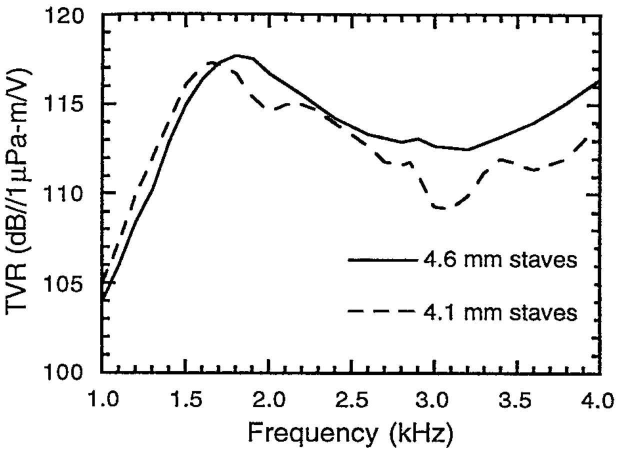

Figure 7. TVR before (solid) and after (dashed) separating the modes by machining the long staves thinner.

-3 dB bandwidth and mechanical quality factor, which includes both peaks, are 920 Hz and 1.8. Hence, the overall increase in bandwidth due to the installation of a butyl boot and the separation of the modes is 61%. As well, the overall decrease in quality factor is 40%. Additional mode separation was not attempted since the dip in the TVR curve between the two peaks would have fallen to more than 3 dB below the value at the larger 1650 Hz peak.

Quality factors of 1.8 are very difficult to obtain with singly-resonant transducers. Clearly, these wide bandwidth, low Q results are consistent with the classification criterion for the broad bandwidth Class III flextensional projectors in the Brigham-Royster classification scheme.

PROJECTOR COMPARISONS

Projectors for sonar applications are designed for high power, low frequency, low Q, and efficient operation. Equally important are the physical characteristics such as low mass and small size. Other factors of importance include depth capability and cost. Although these last two factors are beyond the scope of this paper due to their intrinsic complexities, the performance and physical factors of candidate projectors can be compared to each other for general applicability to modern sonar applications.

Two metrics that are often used to compare projectors are the mass and volume figures of merit FOM_m and FOM_v, where

$$FOM_m \equiv \frac{\text{radiated power (W)}}{\text{mass (kg)} \times \text{frequency (kHz)} \times Q_m}, \quad (4)$$

and

$$FOM_v \equiv \frac{\text{radiated power (W)}}{\text{volume } (m^3) \times \text{frequency (Hz)} \times Q_m}. \quad (5)$$

Table 2. Comparison of various barrel-stave flextensional projectors.

Projector	FOM_m (W/kg-kHz-Q)	FOM_v (W/m^3-Hz-Q)	η (%)
DREA Class III[a] dual-shell	6	19	70
Edo Class I Model 6993	14	49	50
DREA Class II[a] high power	16	49	63
Sparton Class I[a] Model 03BA1100	19	50	74
DREA Class I lightweight	26	63	50
DREA Class I large	47	162	81
NUWC Class I[b] Mod IV Terfenol-D	60	267	15

[a]Projector presented in this paper.
[b]Power limited by stave attachment method.

Note that although these figures of merit appear independent of transducer scaling laws, various electrical, mechanical, acoustic, or manufacturing-related limitations may constrain the scaling ranges of either metric for specific transducer designs.

The two performance metrics and the overall efficiencies for a number of barrel-stave flextensional projectors, including the three presented in this paper, are given in Table 2. More complete details on the Edo Model 6993 projector are found in Moffett and Clay (1993), on the lightweight DREA projector are given by Jones and Lewis (1995b), and on the large high-efficiency DREA projector are given by Jones and Reithmeier (1993) and Jones and Moffett (1993). In addition, a Naval Underwater Warfare Center (NUWC) magnetostrictive Mod IV projector is included in the table since this barrel-stave projector has achieved very high output power levels. Details on this projector are given by Moffett and Clay (1993). The projectors in the table are ordered by the mass figure of merit.

The lowest figures of merit belong to the Class III dual-shell projector presented in this paper. This projector was not designed for low-frequency high-power operation but merely as a research device to investigate multi-resonant bandwidth capability. A new dual-shell barrel-stave projector capable of low-frequency high-power performance is being constructed at DREA at this time.

The Edo Class I, Sparton Class I, and DREA Class II projectors have similar metrics and selecting one over the other for a specific sonar application will depend on the requirements for the individual performance parameters. The improved lightweight DREA Class I projector is similar in size to the Sparton Class I projector, but only weighs 1.5 kg in air. This transducer is useful for air-deployable and neutrally-buoyant sonar applications.

Finally, the large DREA Class I projector, which is about 2 times the size of the Sparton Class I projector, has the best performance parameters to date for a piezoelectric barrel-stave flextensional transducer. Since the figures of merit are close to those of the high-power NUWC permanent-magnet-biased Terfenol-D projector, and the efficiency is more than five times greater, this large piezoceramic projector is an important candidate for modern sonar systems.

CONCLUSIONS

Three barrel-stave flextensional projectors have been presented in this paper. From both the design and performance standpoints, each has been shown to belong to one of the first three classes in the Brigham-Royster classification scheme for flextensional transducers. The Sparton Model 03BA1100 is a Class I flextensional that has been optimized for operation at 1100 Hz. The DREA Class II projector provides 2.5 dB more source level than the Sparton projector due to its extended-stack design. Finally, the DREA Class III projector provides wide bandwidth operation by using a doubly-resonant shell. This projector was able to achieve a low mechanical quality factor of 1.8, which is difficult to do with a singly-resonant design.

REFERENCES

Abbott, F. R., (1959), "Broad Band Electroacoustic Transducer," U. S. Patent No. 2,895,062 (14 July 1959).

Bobber, R. J., (1970), *Underwater Electroacoustic Measurements*, Naval Research Laboratory, Washington D.C.

Boucher, D., (1993), "New Solutions for Low Frequency Sonar Projectors," *Proceedings of the Third International Workshop on Transducers for Sonics and Ultrasonics*, M. D. McCollum et al., ed., Technomic, Lancaster, PA, pp. 17-37.

Brigham, G. A., and Royster, L.H., (1969), "Present Status in the Design of Flextensional Underwater Acoustic Transducers," *J. Acoust. Soc. Am.*, Vol. 46, p. 92.

Butler, J. L., Rolt, K. D., and Tito, F. A., (1994), "Piezoelectric Ceramic Mechanical and Electrical Stress Study," *J. Acoust. Soc. Am.*, Vol. 96, pp. 1914-1917.

Decarpigny, J. N., Hamonic, B., and Wilson, O. B., (1991), "The Design of Low-Frequency Underwater Acoustic Projectors: Present Status and Future Trends," IEEE *J. Oceanic Eng.*, Vol. 16, pp. 107-122.

Hayes, H. C., (1936), "Sound Generating and Directing Apparatus," U. S. Patent No. 2,064,911 (22 December 1936).

Hueter, T. F., (1972), "Twenty Years in Underwater Acoustics: Generation and Reception," *J. Acoust. Soc. Am.*, Vol. 51, pp. 1025-1040.

Jones, D. F., (1993), "Flextensional Barrel-Stave Projectors," *Proceedings of the Third International Workshop on Transducers for Sonics and Ultrasonics*, M. D. McCollum et al., ed., Technomic, Lancaster, PA, pp. 150-159.

Jones, D. F., and Lewis, D. J., (1994), "The Dual-Shell Barrel-Stave Flextensional Projector," Technical Memorandum 94/218, Defence Research Establishment Atlantic, Dartmouth, Nova Scotia, Canada.

Jones, D. F., and Lewis, D. J., (1995a), "The Effects of Shell Wall Thickness and Number of Slots on the Performance of the Merchant Slotted-Shell Flextensional Projector," Technical Memorandum, Defence Research Establishment Atlantic, Dartmouth, Nova Scotia, Canada.

Jones, D. F., and Lewis, D. J., (1995b), "A Lightweight, High-Power, Low-Frequency Barrel-Stave Flextensional Projector," Technical Memorandum, Defence Research Establishment Atlantic, Dartmouth, Nova Scotia, Canada.

Jones, D. F., Lewis, D. J., and Reithmeier, C. G., (1995), "A High-Power Class II Barrel-Stave Flextensional Projector," Technical Memorandum 95/202, Defence Research Establishment Atlantic, Dartmouth, Nova Scotia, Canada.

Jones, D. F., and Moffett, M. B., (1993), "Water Depth and Drive Voltage Dependence of the Acoustic Parameters of a Barrel-Stave Flextensional Projector," *J. Acoust. Soc. Am.*, Vol. 93, p. 2305.

Jones, D. F., and Reithmeier, C. G., (1993) "Low Frequency Barrel-Stave Projectors," *Proceedings of the Undersea Defence Technology Conference*, Reed Exhibition Companies, Tunbridge Wells, Kent, U.K., pp. 251-254.

Klein, E., (1968), "Underwater Sound and Naval Acoustical Research and Applications Before 1939," *J. Acoust. Soc. Am.*, Vol. 43, pp. 931-947.

McMahon, G. W., and Jones, D. F., (1990), "Barrel-Stave Projector," U. S. Patent No. 4,922,470 (1 May 1990); Canadian Patent No. 1,285,646 (2 July 1991).

Merchant, H. C., (1966), "Underwater Transducer Apparatus," U. S. Patent No. 3,258,738 (28 June 1966).

Moffett, M. B., and Clay, W. L., (1990), "High-Power Test of Barrel Stave Flextensional Transducer," Technical Memorandum 901138, Naval Underwater Systems Center, New London, Connecticut, United States.

Moffett, M. B., and Clay, W. L., (1993), "Demonstration of the Power-Handling Capability of Terfenol-D," *J. Acoust. Soc. Am.*, Vol. 93, pp. 1653-1654.

Rolt, K. D., (1990), "History of the Flextensional Electroacoustic Transducer," *J. Acoust. Soc. Am.*, Vol. 87, pp. 1340-1349.

Royster, L. H., (1970), "The Flextensional Concept: A New Approach to the Design of Underwater Acoustic Transducers," *Appl. Acoust.*, Vol. 3, pp. 117-126.

Rynne, E. F., (1993), "Innovative Approaches for Generating High Power, Low Frequency Sound," *Proceedings of the Third International Workshop on Transducers for Sonics and Ultrasonics*, M. D. McCollum et al., ed., Technomic, Lancaster, PA, pp. 38-49.

Toulis, W. J., (1966), "Flexural-Extensional Electromechanical Transducer," U. S. Patent No. 3,274,537 (20 September 1966).

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