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TITLE

LOW FREQUENCY BARREL-STAVE PROJECTORS

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LOW FREQUENCY BARREL-STAVE PROJECTORS

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ABSTRACT

Recently, a number of large barrel-stave projectors, for sonar and general underwater acoustics applications, have been constructed and tested at the Defence Research Establishment Atlantic in Dartmouth, Nova Scotia. The projectors provide high power at low frequency by exploiting mechanical amplification inherent to flextensional transducers. This paper describes the construction of the large barrel-stave projectors and presents the following measured and calculated performance parameters: resonance frequencies, bandwidths, mechanical quality factors, transmitting voltage responses, source levels, and electroacoustic efficiencies. In addition, a simple machining technique for fine tuning the resonance frequencies of the barrel-stave projectors is presented.

INTRODUCTION

Extensive research into low frequency sonar transducers at the Defence Research Establishment Atlantic (DREA) has led to the development of a number of flextensional barrel-stave projectors. Over the last seven years DREA has investigated at least five significantly different barrel-stave designs. In all, DREA has constructed and calibrated more than seventy barrel-stave projectors based upon these designs. About one third of the barrel-stave projectors have been assembled into research systems that have been deployed at sea from DREA's research ship CFAV Quest.

The purpose of this paper is to discuss one of these designs, namely, the large barrel-stave projector, which is approximately twice the size of the original DREA barrel-stave projector patented by McMahon and Jones (1). The geometry of the main components of the large projector is described first. This is followed by the presentation and discussion of the key performance parameters of five experimental projectors. These parameters are extracted from the measured electroacoustic calibration data obtained at the DREA acoustic calibration facility. Finally, a practical procedure for fine tuning the resonance frequencies of the barrel-stave projectors is described.

CONSTRUCTION

A cross-sectional view of the large barrel-stave projector is shown in Figure 1. The size shown is approximately 1/4 scale. The active driver consists of a stack of fourteen axially poled, Navy Type I, lead zirconate titanate piezoceramic rings. Each ring has a 9.0 cm outside diameter, a 2.0 cm wall thickness, and a 1.4 cm height. The rings are bonded together using epoxy adhesive and connected in parallel, electrically. The wiring harness (not shown) is located inside the stack. The outside of the stack is fiberglass wrapped for shock hardening, corona suppression, and moisture protection.

Bonded to each end of the ceramic stack is an octagonally shaped end plate made from carbon steel 1020. The length of a plate side is 6.0 cm and the plate thickness is 2.5 cm. Holes, 2.5 cm in diameter and passing through the centers of the plates, accommodate the smaller diameter portions of the end caps and allow the electrical leads to exit the

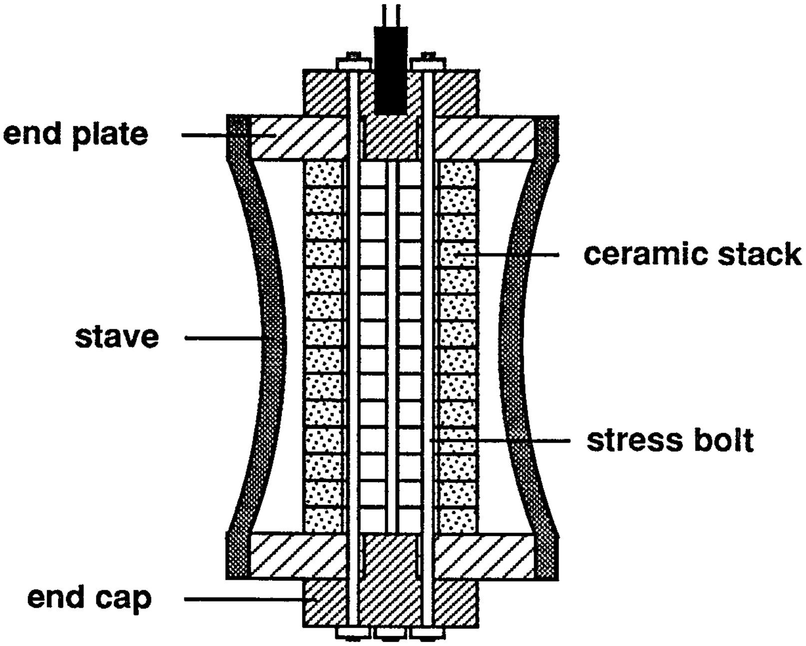

Figure 1: Cross-sectional view of the large barrel-stave projector.

interior of the projector. Four 5 mm diameter holes, symmetrically placed about the central hole in each plate, allow stress bolts (three are shown) to pass through the plates.

Two aluminum 6061 end caps are bonded to the outside surfaces of the end plates. The top end cap (in the figure) has holes in the center so that the electrical leads can exit the projector. The holes and leads are potted with epoxy. The diameter and thickness of the large external portions of the end caps are 8.9 cm and 2.5 cm, respectively. The end caps were used to support the projectors in the water during the calibration measurements.

Four stainless steel 304 stress bolts, 4.8 mm in diameter, are fastened to the end caps under tension, providing a compressive bias to the ceramic stack. This bias need only be large enough to prevent the stack from going into tension during testing in air or shallow water, since the bias is enhanced in water by hydrostatic pressure due to the concave curvature of the staves. This is one of the advantages of the barrel-stave design over other flextensional transducer designs such as the Class IV flextensional transducer discussed by Oswin and Dunn (2).

Eight aluminum 7075 staves are screwed and bonded to the end plates. The staves are 24.8 cm in length, 6.4 cm wide at the ends, and have average thicknesses ranging from 7 to 11 mm. The radii of curvature of the inside and outside surfaces of the staves are both 28.3 cm. Eight longitudinal gaps stretching from one plate to the other, separate adjacent staves by 1 mm. These gaps should be as small as possible to maximize the radiating surface area of the projector, but large enough to ensure that adjacent staves do not come in contact at full drive and at the operating depth.

To prevent the ingress of seawater through the gaps and into the air cavity between the staves and the stack, a cylindrical neoprene 5109-S rubber boot, moulded at DREA, is stretched over the projector and bonded to the outside surfaces of the end plates. The unstretched rubber boot has the following dimensions: 11.4 cm inside diameter, 1 mm wall thickness, and 30 cm length. In air, the weight of the fully assembled projector is 17 kg, however, it is possible to substantially reduce this weight by using aluminum rather than steel end plates.

During operation at the fundamental mode of vibration, the stack, end plates, and end caps vibrate axially, causing the staves to flex radially. Since the entire outside surface of the barrel-stave projector vibrates in phase, the projector is an efficient radiator of sound. Further discussion of this relationship between the phase of the displacements and the radiating efficiency of flextensional transducers is found in Pagliarini and White (3).

MEASUREMENTS AND CALCULATIONS

Five large barrel-stave projectors were tested in seawater at the DREA acoustic calibration facility. In this paper, these projectors are referred to by the names DREA-1 to DREA-5. The only significant difference between the projectors is that DREA-1 has an average stave thickness of 7 mm while the other four projectors have an average stave thickness of 8 mm. The transmitting voltage response (TVR), electrical conductance (G), and electrical susceptance (B) were measured for each projector at the two water depths of 14.6 m and 30.0 m. The results for DREA-3 in 30.0 meters of seawater are shown in Figures 2 and 3. These results are typical of all five projectors at both depths of interest.

Various performance parameters can be determined from the measured conductance curves like the one shown in Figure 2. For example, the resonance frequency, f_r, is the frequency associated with the maximum in the conductance curve, G_{max}. The bandwidth is the difference between the upper and lower frequencies, f_u and f_l, where G falls to one half G_{max}. And the mechanical quality factor, Q_m, is given by the ratio of the resonance frequency to the bandwidth as follows:

$$Q_m = \frac{f_r}{f_u - f_l} \quad (1)$$

The source level, SL, is calculated from the TVR curves, like the one shown in Figure 3, by using the expression

$$SL = TVR + 20 \log (V_{in}) , \quad (2)$$

where V_{in} is the rms input driving voltage.

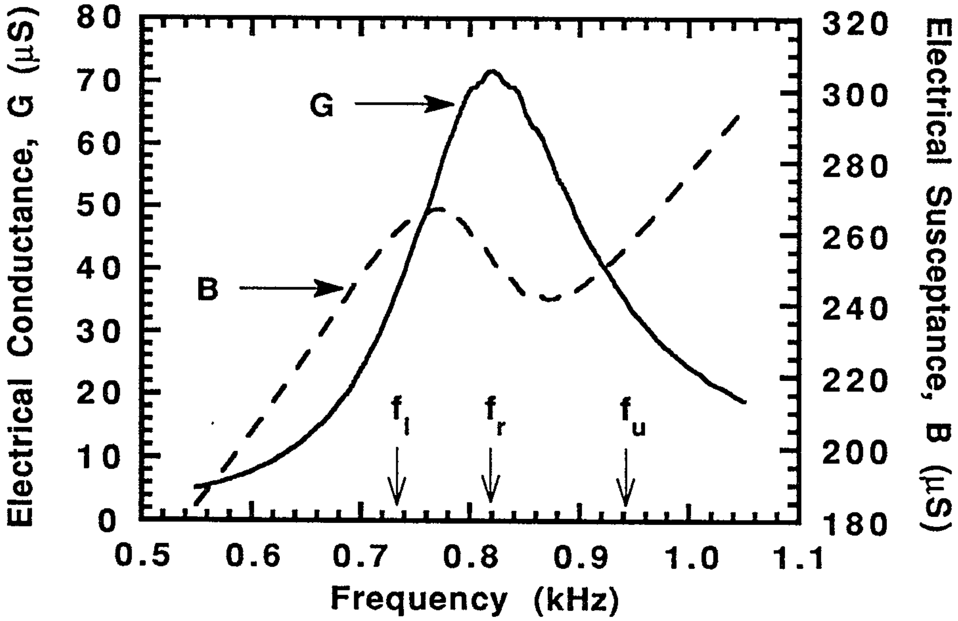

Figure 2: G and B of barrel-stave projector DREA-3 at 30.0 m.

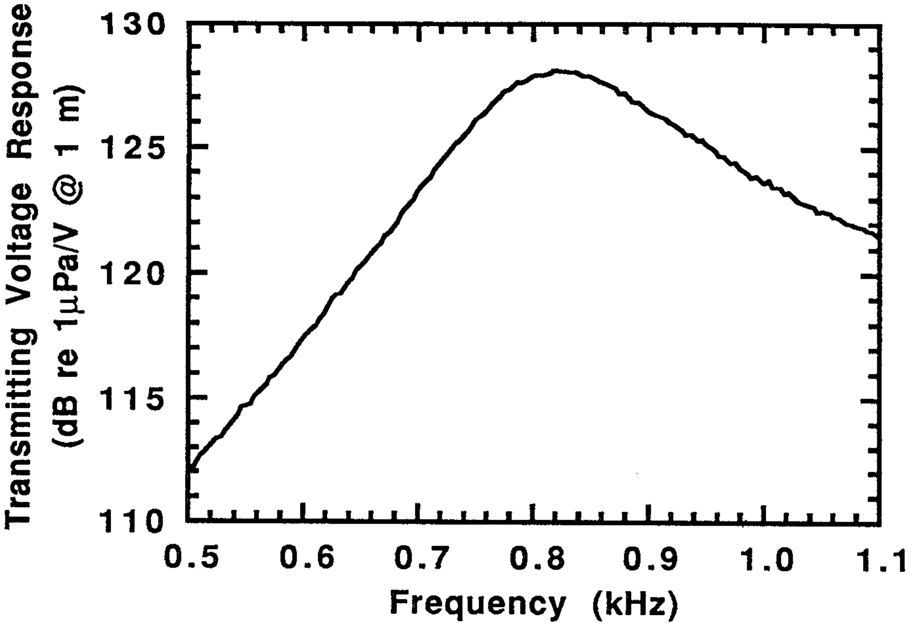

Figure 3: TVR of barrel-stave projector DREA-3 at 30.0 m.

The electroacoustic efficiency, η, expressed in percent, is obtained from the equation

$$\eta = 100\% \times 10^{0.1 \times (\mathrm{TVR} - \mathrm{DI} - 170.8 - 10 \log G)} , \qquad (3)$$

where the G and TVR are the measured parameters determined from curves like those in Figures 2 and 3, and DI is the measured directivity index. The directivity indices are assumed to be zero for all five of the barrel-stave projectors in this paper since they are nearly omnidirectional at their fundamental resonance frequencies.

The measured and calculated parameters for the five large barrel-stave projectors are listed in Tables 1 and 2 for the water depths of 14.6 m and 30.0 m, respectively. The values for the transmitting voltage responses, source levels, and electroacoustic efficiencies correspond to the resonance frequencies listed in the second column of the tables. The source level is calculated for V_{in} equal to 5.5 kV_{rms}. This input driving voltage generates an electric field of 3.9 kV_{rms}/cm (9.9 V_{rms}/mil) in the piezoelectric rings, which, according to Woollett (4), is an acceptable electric field limit for piezoelectric ceramic materials. The complete decibel unit specifications for TVR and SL are as follows:

$$\mathrm{TVR}\ (\mathrm{dB\ re\ 1\mu Pa / V\ @\ 1\ m}) \quad \text{and} \quad \mathrm{SL}\ (\mathrm{dB\ re\ 1\mu Pa\ @\ 1\ m}) .$$

projector	f_r (Hz)	$f_u - f_l$ (Hz)	G_{max} (μS)	Q_m	TVR (dB)	SL (dB)	η (%)
DREA-1	790	220	68	3.6	128	203	76
DREA-2	810	260	68	3.1	128	203	73
DREA-3	810	200	70	4.1	128	203	75
DREA-4	810	200	69	4.0	128	203	72
DREA-5	820	210	67	4.0	128	203	78

Table 1: Projector performance parameters at 14.6 m depth.

projector	f_r (Hz)	$f_u - f_l$ (Hz)	G_{max} (µS)	Q_m	TVR (dB)	SL (dB)	η (%)
DREA-1	810	260	63	3.1	127	202	73
DREA-2	840	260	57	3.2	127	202	71
DREA-3	820	210	72	4.0	128	203	74
DREA-4	830	220	65	3.8	128	202	73
DREA-5	830	220	67	3.8	128	203	76

Table 2: Projector performance parameters at 30.0 m depth.

DISCUSSION

From Tables 1 and 2 it is evident that DREA-1 has a lower resonance frequency than the other four projectors for a given water depth. This can be attributed to lower stiffness in the DREA-1 staves, since they are 1 mm thinner than the staves of the other projectors.

In discussing the changes in the performance parameters with depth, consider the average parameter changes for the five projectors in Tables 1 and 2. The average increase in the resonance frequency, as the depth is changed from 14.6 m to 30.0 m, is 20 Hz. The associated average decrease of 0.2 in the quality factors is qualitatively consistent with this frequency change. However, the 1% and 0.4 dB average decreases in the respective values of efficiency and TVR at resonance, are not consistent with the frequency increase.

One plausible explanation for these observed changes, however small, is that rubber is being forced into the inter-stave gaps by hydrostatic pressure. The result is an increase in hoop stiffness and, as a consequence, an increase in resonance frequency. At the same time, the staves become partially clamped by the physical contact with the rubber in the gaps, causing a decrease in volume velocity, and hence, output power and efficiency. Further investigations of the depth dependencies of the performance parameters of the large barrel-stave projectors have been reported by Jones and Moffett (5).

The projector DREA-1 was calibrated twice to determine the effects of stave thickness on the performance parameters of the large barrel-stave projectors. The staves were originally machined to an average thickness of 11 mm. The projector was booted and calibrated in 30.0 m of seawater. The results are given in the first row of Table 3.

After this first calibration, the rubber boot was removed and the projector was mounted on a tracer lathe. The gaps between the staves were filled with duct-seal putty to prevent aluminum shavings from entering the projector. The outside surface of the aluminum staves was machined down until the average thickness of 7 mm was reached. The duct-seal putty was removed from the gaps and a new boot was installed on the projector.

The projector was recalibrated in 30.0 m of seawater. The results appear in Table 2 and are repeated in the second row of Table 3 for comparative purposes. The 100 Hz reduction in the resonance frequency of DREA-1, after the 11 mm staves were machined down to 7 mm, is useful for tuning the large barrel-stave projectors. If a linear relationship is assumed, the change in resonance frequency with stave thickness is about 25 Hz/mm. This change predicts an 835 Hz resonance frequency for DREA-1 with 8 mm staves, which agrees with the resonance frequencies of DREA-2 to 5, whose staves are 8 mm thick and whose resonance frequencies fall in the range 820 to 840 Hz (see Table 2).

stave thickness (mm)	f_r (Hz)	$f_u - f_l$ (Hz)	G_{max} (μS)	Q_m	TVR (dB)	SL (dB)	η (%)
11	910	260	48	3.5	126	201	71
7	810	260	63	3.1	127	202	73

Table 3: The effects of stave thickness on the acoustic parameters of DREA-1 at 30.0 m.

CONCLUSIONS

Five large barrel-stave projectors have been built and tested at DREA. A detailed account of their construction has been given. The measured acoustic performance parameters at two depths in seawater have been presented and discussed. The dependence of these parameters on depth has been qualitatively explained in terms of interactions between the rubber boot and the gaps between the staves. In addition, the dependence of resonance frequency on stave thickness has been determined. This dependence can be used to tune the barrel-stave projector by mounting the unbooted projector on a tracer lathe, and then machining the staves down to a thickness that will yield the desired resonance frequency, according to an empirically determined relationship between frequency and stave thickness.

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