TITLE

THE ACOUSTIC PERFORMANCE OF A CLASS III BARREL-STAVE FLEXTENSIONAL PROJECTOR

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ABSTRACT

A new broadband Class III barrel-stave flextensional projector has been built and tested for low-frequency sonar applications at the Defence Research Establishment Atlantic (DREA). The electroacoustic performance parameters of this projector were measured at the DREA Acoustic Calibration Facility on nearby Bedford Basin. This paper describes the construction of the double-shell Class III projector, presents its measured performance parameters, and compares its performance to that of a single-shell Class I barrel-stave projector of similar design. The Class III projector exhibits a mechanical quality factor of 2.1 near its fundamental flexural resonance frequency, which is lower than the quality factors normally produced by the other flextensional classes. In addition, useful acoustic power output is obtained from the Class III projector throughout the frequency range 1.1-7.5 kHz due to close coupling between the fundamental flexural mode and higher frequency radiating modes.

INTRODUCTION

According to the flextensional transducer classification scheme devised by Brigham and Royster (1), the barrel-stave flextensional sonar projector, invented at the Defence Research Establishment Atlantic (DREA) in the late 1980s by McMahon and Jones (2), is a Class I flextensional transducer. In essence, this projector consists of a piezoceramic ring-stack driver that is electrically excited into extensional vibration, causing a surrounding set of concave aluminum staves to vibrate in flexure through mechanical leverage. In this way, low-frequency high-power sound is generated from a compact transducer. Typical performance parameters for a number of Class I barrel-stave flextensional designs are presented in the review paper by Jones (3).

For a given resonance frequency and source level, it is sometimes desirable for a flextensional projector to have a lower mechanical quality factor than that which can normally be obtained with singly-resonant transducers. For example, quality factors in the range 1-3 may be preferred over quality factors in the range 3-6, the latter range being characteristic of most flextensional designs such as those discussed in the review paper by Jones and Lindberg (4). One technique that is used to significantly reduce the quality factor is to employ a doubly-resonant shell design like the Class III flextensional transducer discussed by Royster (5). The shell of this transducer has two closely coupled resonance modes that combine to give a broadband response in water.

A doubly-resonant Class III barrel-stave flextensional projector constructed with two different sets of staves was previously studied by Jones et al. (6). In that work it was shown that this Class III design could achieve mechanical quality factors below 3 by optimally separating the coupled flexural modes of the two sets of staves. In this paper it is shown that a low quality factor can be obtained from a Class III barrel-stave projector with two identical sets of staves. Furthermore, it is observed that the proximity of the fundamental flexural mode with the higher frequency radiating modes significantly improves the overall wideband response. Finally, the staves are modified to produce a doubly-resonant shell with a further reduction in the quality factor near resonance.

PROJECTOR CONSTRUCTION

The Class III barrel-stave flextensional projector is illustrated in a cutaway view in Figure 1. The driver consists of two stacks made from axially-poled Navy Type III lead zirconate titanate piezoceramic rings with the following dimensions: 5.08 cm outside diameter, 5.6 mm wall thickness, and 1.02 cm height. Each stack has 10 rings, which are bonded together and connected in parallel electrically. One end of each stack is bonded to the opposite sides of a 2.54 cm thick carbon steel center plate while the other ends of the stacks are bonded to 1.27 cm thick carbon steel end plates. All three plates have octagonal cross-sections of side length 3.0 cm to facilitate stave attachment. Aluminum end caps with outside diameters of 5.08 cm and heights of 1.27 cm are fastened to the end plates and provide support for the electrical leads and four internal stainless steel prestress rods (not shown). Sixteen identical curved aluminum staves are attached to the flat edges of the steel plates. Each stave is 12.7 cm long, has a 5 mm maximum thickness in the center, has a radius of curvature of 20 cm, and is separated from adjacent staves by a 1 mm wide gap. A 1 mm thick neoprene 5109-S rubber boot (not shown) is stretched over the staves and is bonded in place on the two end plates in order to maintain pressure release conditions on the inside surfaces of the staves. The maximum outside diameter of the fully assembled projector is 8.5 cm, the overall length is 28 cm, and the mass is 3.9 kg.

The Class I barrel-stave flextensional projector, included in this paper for comparative purposes, is basically one half of the Class III design as shown in Figure 2. A single stack of ten axially-poled Navy Type I lead zirconate titanate piezoceramic rings is bonded to two steel end plates, and eight curved aluminum staves are attached to the sides of these plates. A single tie rod prestresses the ceramic rings and a neoprene 5109-S rubber boot prevents seawater ingress. The dimensions of the Class I ceramic rings, end plates, end caps, and aluminum staves are the same as those of the respective Class III components. The maximum outside diameter of the fully assembled projector is 8.5 cm, the overall length is 15 cm, and the mass is 2.0 kg. Further details concerning the construction of Class I and III barrel-stave flextensional projectors can be found in Jones (7).

PROJECTOR PERFORMANCE

The performance parameters of the Class I and Class III barrel-stave flextensional projectors were determined from measurements made in 14.6 m of seawater at the DREA Acoustic Calibration Facility using standard calibration techniques described in Bobber (8). All of the measurements were taken with applied electric fields not exceeding 100 Vrms/cm and included the electrical conductance and susceptance, the transmitting voltage response, and the vertical (XZ) directivity pattern at resonance. The results for the Class III projector are shown in Figures 3 to 5. Similar measurements were obtained for the Class I projector but are not shown here. Using these measurements, and the guidelines for specifying the performance parameters of underwater transducers conveniently summarized by Kuntsal and Bunker (9), the resonance frequency (f_r), electrical conductance (G_r) at resonance, -3 dB bandwidth (BW), mechanical quality factor (Q_m), transmitting voltage response (TVR_r) at resonance, directivity index (DI_r) at resonance, and the electroacoustic efficiency (η_r) at resonance were determined. A summary of these electroacoustic performance parameters for both barrel-stave flextensional projectors is given in Table 1.

PROJECTOR COMPARISON

The fundamental flexural resonance frequencies of the Class I and III projectors given in Table 1 are 1340 Hz and 1390 Hz, respectively. These frequencies are similar since the geometry and material properties of the aluminum staves, which are identical for both projectors, primarily govern the resonance frequencies of the transducers' flexural modes. The 50 Hz difference is due to greater effective stiffness in the Class III driver, which takes into account both the higher elastic modulus of Type III over Type I ceramic and the increased stiffness of the thick steel center plate compared to that of the thinner end plate on the Class I projector.

For a given applied electric field, the ratio of acoustic power handling capacities between the Class III and Class I projectors can be estimated since power handling is proportional to the product $\varepsilon V f_r Q_m k^2$, where ε and V are the dielectric constants and volumes of piezoceramic, and f_r, Q_m, and k are the fundamental resonance frequencies, mechanical quality factors, and coupling coefficients of the projectors [see Stansfield (10)]. For the Class I and III projectors, the dielectric constants for the respective Type I and III piezoceramics are approximately 1350 and 1150 (from the manufacturers' datasheets). The Class III projector has twice the ceramic volume of the Class I projector. The resonance frequencies and mechanical quality factors for the two projectors are found in Table 1. The coupling coefficients of the Class I and III projectors, determined from the measurement of electrical admittances in air and the equations found in Woollett (11), are 0.26 and 0.33 respectively. Therefore, the ratio of the power handling products predicts a 1.5 dB improvement in acoustic output for the Class III projector. As can be seen from the TVR values in Table 1, this is precisely the observed TVR advantage of the Class III projector over the Class I projector at their respective resonance frequencies.

The significant increase in electroacoustic efficiency from 54% for the Class I barrel-stave projector to 80% for the Class III projector may be due to the stiff center plate of the Class III projector. Since the center plate on the Class III projector is acted upon symmetrically by a ceramic stack and a set of aluminum staves on either side, the center plate is less susceptible to plate flapping than an end plate. Thus, the stack motion is more efficiently converted into stave motion in the Class III projector. This explanation is consistent with the observation that the coupling factor of the Class III projector is greater than that of the Class I projector.

The reduction in mechanical quality factor from 4.2 for the Class I projector to 2.1 for the Class III projector can be attributed to three factors. In order of decreasing influence, the Class III projector has twice the radiating surface area, more coupling from higher radiating modes, and a higher flexural resonance frequency. The influence of the higher radiating modes is evident in the TVR curves of Figure 6.

In water, the Class I barrel-stave flextensional projector has three significant radiating modes below 10 kHz. They can be identified in Figure 6 as the fundamental flexural mode at 1340 Hz, an overtone flexural mode at 6930 Hz, and the extensional stack mode at 8060 Hz. Finite element analysis predicting the presence of these types of modes for low frequency barrel-stave flextensional projectors is given by Yao and Bjørnø (12). Since the stave geometry and properties primarily determine the frequencies of the flexural modes and the length of the driver strongly influences the frequency of the extensional mode, then the Class III projector, being about twice the length of the Class I projector, will have flexural mode frequencies similar to those of the Class I projector but a lower extensional stack mode frequency. This is observed in Figure 6, where the Class III extensional stack mode occurs at 5440 Hz but the flexural modes have remained essentially unchanged (the overtone flexural mode is the shoulder on the high frequency side of the large extensional mode peak). The extensional mode and fundamental flexural mode peaks are coupled in the Class III projector, which is the reason for the wideband response from about 1.1 kHz to 7.5 kHz. In this band, a maximum TVR improvement of 20 dB occurs at 3.8 kHz.

Finally, it is a simple matter to modify the Class III projector to produce two closely coupled flexural modes with frequencies and TVR values close to those of the fundamental flexural mode of the Class I projector. This is accomplished by mounting the Class III projector on a tracer lathe and machining 1.2 mm of aluminum off one set of staves. Since this thinner set of staves is more compliant than the thicker unmachined set of staves, the thinner set has a lower flexural mode resonance frequency than the thicker set. Thus these two closely coupled flexural modes further broaden the low frequency response. The TVR curves for the Class I projector and this doubly-resonant Class III projector are shown in Figure 7. Note that the TVR values of both projectors at 1340 Hz is 121.5 dB//1μPa-m/V, but the mechanical quality factors are 4.2 and 1.5 for the Class I and III projectors, respectively. This is a significant reduction from the 2.1 quality factor obtained with the unmachined Class III projector.

CONCLUSIONS

The construction and electroacoustic performance of a new broadband low-frequency Class III barrel-stave flextensional projector have been presented in this paper. The Class III projector significantly outperforms its Class I counterpart by achieving a low mechanical quality factor of 2.1 and a high electroacoustic efficiency of 80%. It has also been shown that by modifying the thickness of the concave staves, a doubly-resonant Class III configuration is obtained, further reducing the mechanical quality factor to 1.5 at low frequencies. Finally, since the Class III projector is longer than the Class I projector, the low-frequency fundamental flexural mode is coupled to higher frequency flexural and extensional modes producing a useful wideband response from about 1.1 kHz to 7.5 kHz.

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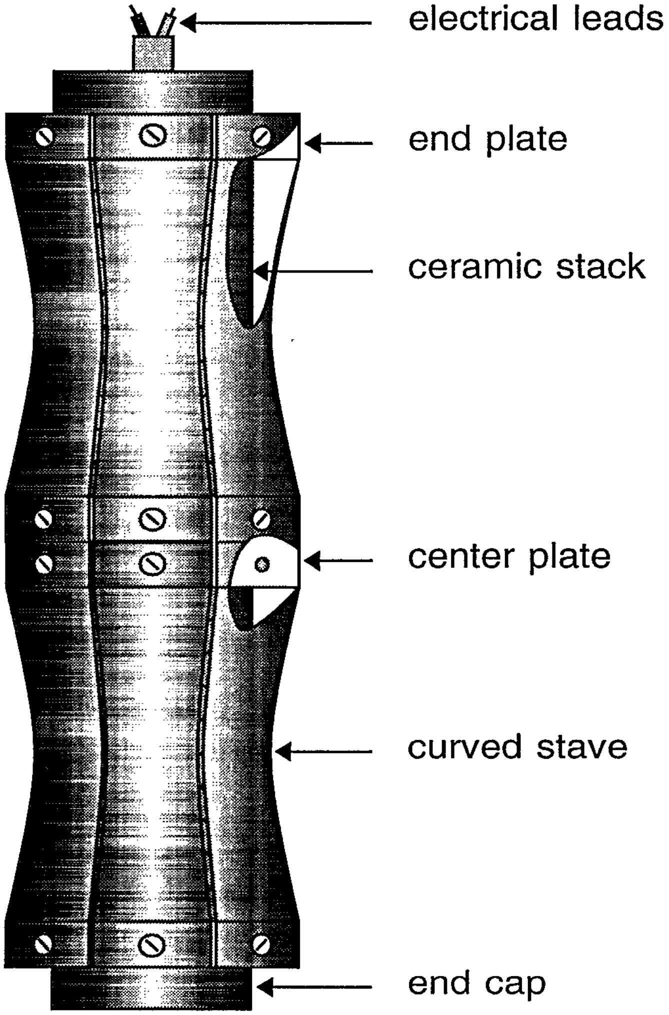

Figure 1. Cutaway view of the Class III barrel-stave flextensional projector.

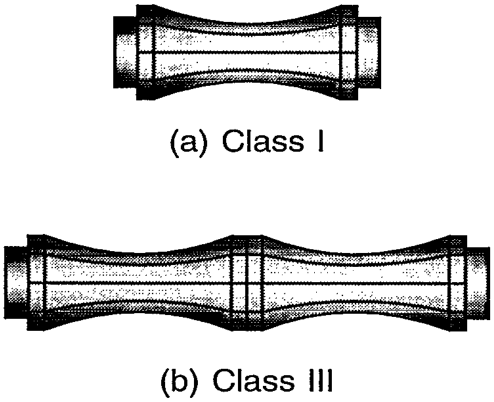

Figure 2. Class I (a) and Class III (b) barrel-stave flextensional projectors.

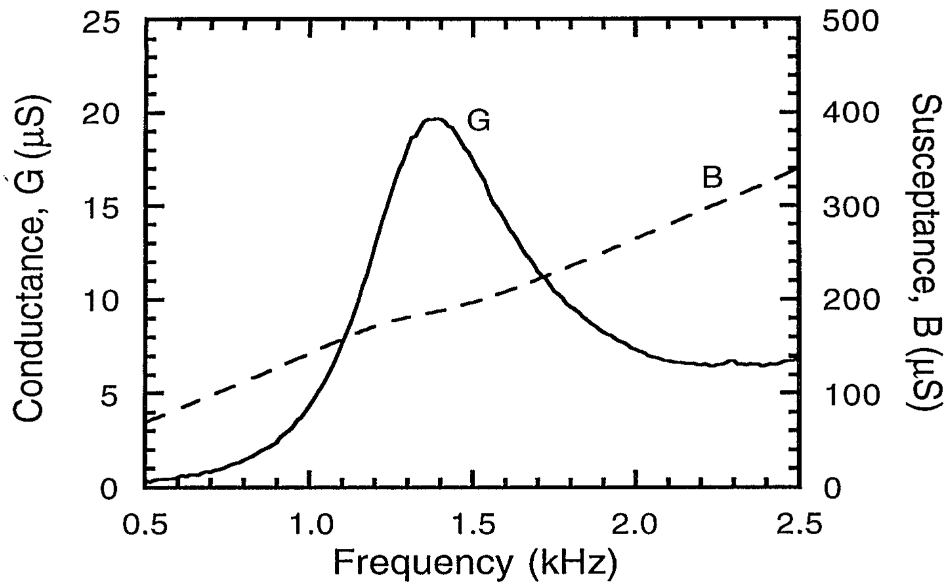

Figure 3. Conductance (G) and susceptance (B) of the Class III projector in seawater.

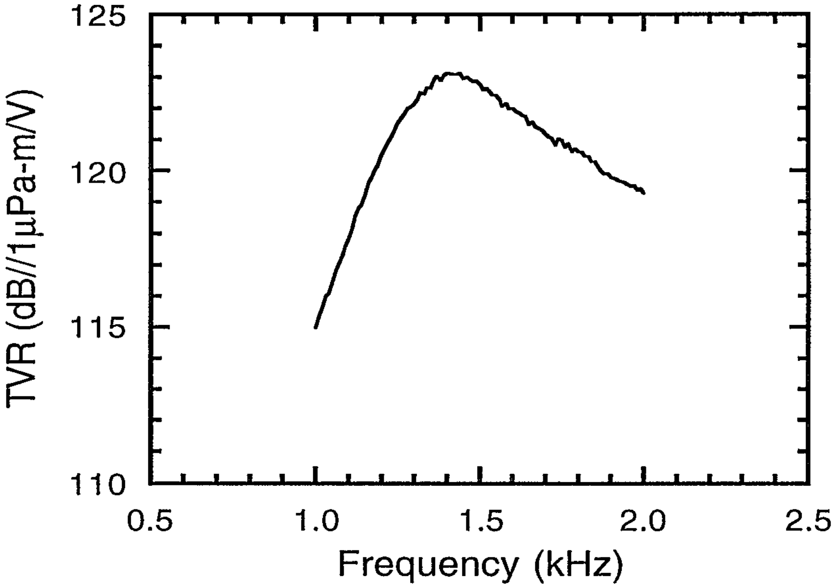

Figure 4. Transmitting voltage response (TVR) of the Class III projector in seawater.

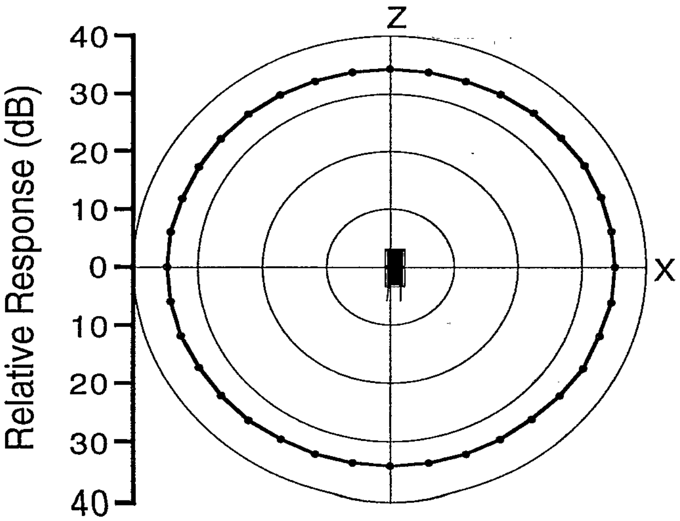

Figure 5. Vertical (XZ) plane directivity pattern of the Class III projector at resonance.

Table 1. Performance parameters for the Class I and Class III barrel-stave flextensional projectors.

Projector	f_r (Hz)	G_r (μS)	BW (Hz)	Q_m	TVR_r^* (dB)	DI_r (dB)	η_r (%)
Class I	1340	21.1	320	4.2	121.5	0.16	54
Class III	1390	19.6	660	2.1	123.0	0.26	80

*Note that the full unit specification for TVR is dB//1μPa - m / V.

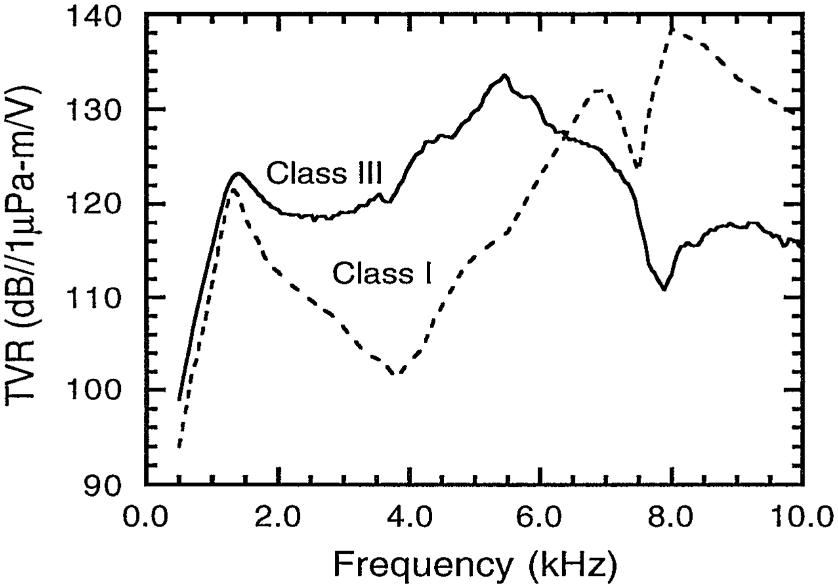

Figure 6. TVR curves of the Class I and Class III barrel-stave projectors in seawater.

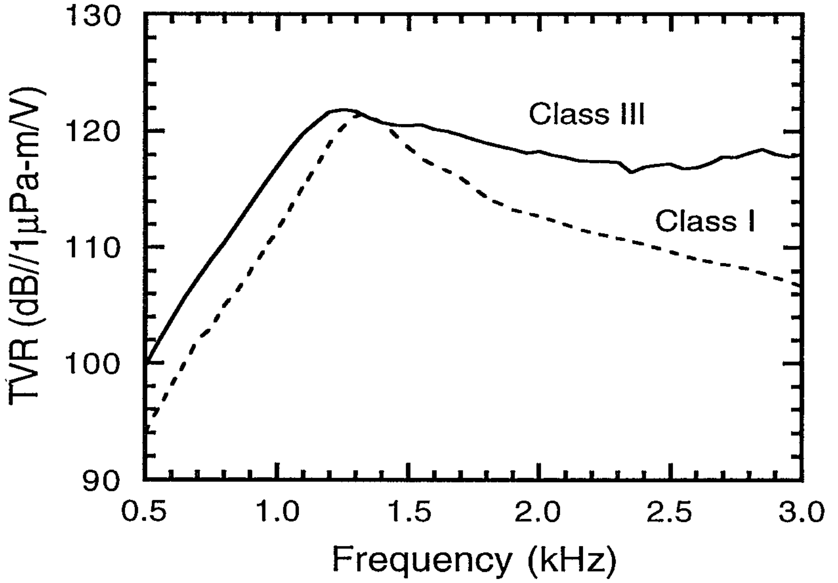

Figure 7. TVR for the Class I and doubly-resonant Class III projectors in seawater.

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