SLOTTED CYLINDER PROJECTORS

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1. INTRODUCTION

The Slotted Cylinder Projector (SCP) is a compact source which produces moderate acoustic output at low frequencies. A typical SCP consists of a cylindrical shell with a slot cut axially along its length. The slot drastically reduces the hoop stiffness, so that the familiar breathing radial resonance is lost and replaced by a flexural mode. The operation is akin to that of a flexural bar transducer. As with other types of flexural transducer, the flexing mode can only be excited electrically by mounting piezoelectric ceramic on the passive shell. A typical SCP design is shown in Figure 1.

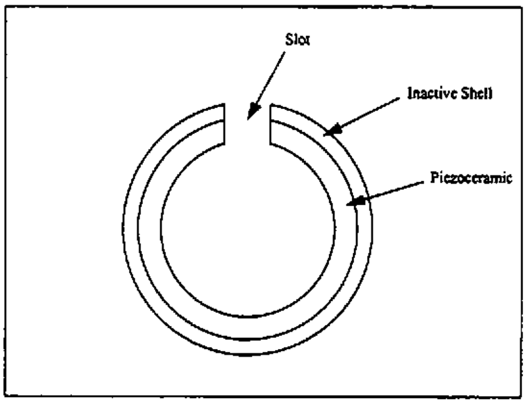

Figure 1; Typical SCP Design

The purpose of this paper is to demonstrate the operation of the SCP and explore the parameters which limit performance. Containment of an internal air space and mechanical stressing of the transducer for operation at depth are an integral part of the design, however only acoustic performance is considered here. This is done by demonstrating the physical operation of the device in simplified form and modelling performance using finite element (FE) and boundary element (BE) techniques. The modelling predictions are used to indicate the performance envelope which may be expected of these transducers for a given dimensional constraint. It is impractical to make a number of SCP devices to gauge performance, so the "experimentation" for this paper has been carried out using the PAFEC FE/BE code [1].

2. SLOTTED CYLINDER PROJECTOR

The nominal design aim, without prior knowledge of the device, was to produce a 1kHz transducer using a ceramic of 114mm diameter (a standard DERA size) and 114mm height. It was recognised that the operation of the device may be limited by the physics of its operation. This study examines whether the design aim can be achieved. Under these design conditions, the transducer's dimensions are less than one tenth of its radiating wavelength, so it radiates essentially as a point source. This also means that a large volume displacement is essential for good radiation performance.

Although it is vital to assess performance by resonant frequency and Transmit Voltage Response (TVR) (or maximum conductance) at resonance, this does not necessarily provide complete diagnostic data for understanding the design criteria. It is useful for performing comparisons between SCP designs to look at the output well below resonance (at 100Hz, say) and also to observe the displacement at positions along the flexing "arms" of the device to understand how the flexure contributes to the output.

3. THE PHYSICS SIMPLIFIED

The easiest way to understand the operation of the SCP is to "unwrap" it so that it resembles a thick flexural bar vibrating with free ends [2]. The resonant frequencies *in-vacuo* can be determined from the vibrating length, ℓ (the circumference less the slot size) and the combined thickness of the ceramic and elastic shell layers:

$$f = (\pi\, c\, \kappa / 8\, \ell^2)\, (S)^2$$

where: S is a value from a series 3.0112, 5, 7, 9, ...;

κ^2 represents a radius of gyration $t^2/12$ (t = thickness);

$c^2 = Y / \rho$ (Y = Young's Modulus, ρ = density).

Higher S values pertain to higher modes of vibration. These give resonant frequencies more appropriate for the size of the device. Unfortunately these involve phase reversal of displacements along the length of the bar, resulting in a low net volume displacement.

Having set the circumference to approximately 340mm, the thickness required to give a resonant frequency of 1kHz can be determined. For materials such as ceramic and those with similar moduli, a thickness of 25-30mm is necessary. Although this would be split into two layers - ceramic and shell, it is still impracticably thick to build, so it is likely that any transducer based on these dimensions is likely to operate at a lower frequency. This is unfortunate, as it increases the need for volume displacement to generate useful output powers.

The volume displacement generates acoustic power in miniature sources according to [2]:

$$\text{Power} = 2\, \pi^3\, (\rho/c)\, f^4\, A^2$$

Where: A = volume displacement amplitude (zero-to-peak);

ρ = density of the radiating medium;

c = sound speed of the radiating medium;

A is determined by the integrated displacement along the length of the arms, so by increasing the amplitude of movement of the arms and ensuring that there is no out-of-phase displacement, power output is raised at a given frequency.

The resonant frequency can be increased by shortening the length of the arms. The construction process would be much simpler if the SCP could be made from two pieces each just less than semi-circumferential. However, the displacement is much reduced as the length-to-thickness ratio is decreased and the linear momentum advantage is also lost. Indeed, a small negative-going displacement is observed near the axis, which reduces the integrated displacement further. Output power is therefore drastically reduced.

A possible design improvement is to introduce a taper to the shell. The effect of the tapering, demonstrated in Section 5 of this paper, appears to raise the resonant frequency above that of the maximum thickness while maintaining the displacement pattern appropriate to the minimum shell thickness, thereby giving a much higher frequency for a given size.

4. FE/BE MODELLING

The ceramic component of the SCP design has been modelled as a stack of 4 DERA Test Rings (total height 114mm), with a slot cut into them, in order to identify the mechanism behind the transducer's operation. The DERA Test Ring is a simple Navy I radially poled piezoceramic ring [3]. It has dimensions as follows:

- Outer radius 57.17mm;
- Inner radius 50.8mm;
- Axial height 28.0mm.

The FE method is used to describe the structure and incorporates piezoelectric coupling. A perfect joint is assumed between the ceramic and the elastic shell. The surrounding acoustic fluid is described using BEs. Coupling between the fluid and the structure is enforced by applying the correct continuity relations. TVR, admittance data and far-field directivities may be calculated from the Helmholtz Solution for a hybrid FE/BE model. Since the device is not axisymmetric, it was necessary to model the structure using 3-D FEs.

A further consideration is the boundary condition on the internal surface of the SCP. Analysis shows that the transducer needs differential boundary conditions between the inner surface and the outer surface (i.e. the transducer should be air-backed). In practical terms this would be achieved by having endcaps and a compliant seal over the slot. To simplify the modelling, this was achieved by simply specifying a surface admittance condition of zero pressure on the inner surface of the device via the PAFEC absorbency module. Recent work has shown that this may give pessimistic TVR results by about 3dB, but all results quoted here are based on this analysis.

A frequency of 100Hz has been chosen as the standard for comparison between the various SCP configurations as it is significantly below all resonances. As a first diagnostic, the TVR of the transducer at 100Hz is an indication of its suitability as a power source, but more detailed information can be gained from observing the displacement pattern along the arms.

5. ANALYSIS

Table 1 details the results of the FE/BE modelling exercise. Aluminium was used throughout for the elastic shell. Again, other materials such as carbon fibre composite could have been chosen to alter the resonant frequency but a restricted scope has been placed on this study.

The displacement figure quoted is the sum of the linear displacements of individual positions along the arm. It is therefore related to the volume displacement and thus the acoustic power output for 1V drive at that frequency.

Model	Res Freq (Hz)	TVR @ res (dB re 1μPa/V @ 1m)	TVR @ 100Hz (dB re 1μPa/V @ 1m)	Displ @ 100Hz (m)
Case 1: 6mm ceramic, 0mm shell, 9/9 of structure modelled	178	81.6	60.2	4.0E-8
Case 2: 6mm ceramic, 6mm shell, 9/9 of structure modelled	323	110.3	71.8	1.6E-7
Case 3: 6mm ceramic, 12mm shell, 9/9 of structure modelled	458	115	70.3	1.1E-7
Case 4: 6mm ceramic, 6mm shell, 4/9 of structure modelled	1661	115.5	37.6	1.0E-8
Case 5: 3mm ceramic, 3mm shell, 4/9 of structure modelled	954	113.4	48.1	3.2E-8

Table 1; Results for various SCP device configurations

It is seen that increasing the thickness of the ceramic and shell raises the resonant frequency which increases the TVR at resonance even when the displacement is reduced (because of the f^4 term in the power output). As implied before, the frequency can be raised rapidly by shortening the length of the arms, but the device becomes much stiffer with consequent drastic reduction in volume displacement so with no gain in TVR.

The displacement pattern is shown for Case 2 in Figure 2 below. The undeformed structure is shown in solid lines, with the deformed structure in dashed lines.

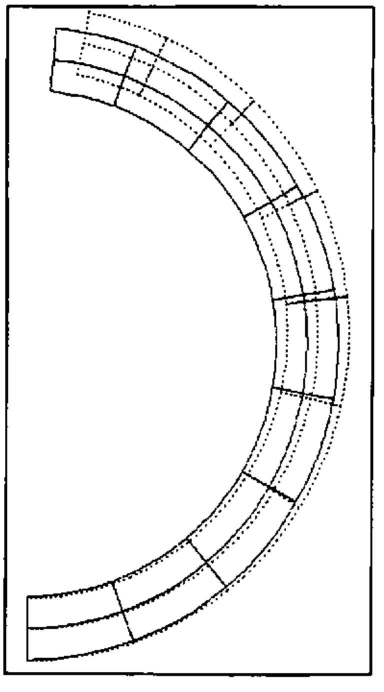

Figure 2; Displacement pattern for Case 2

Figure 3 compares the displacement at various positions along the arm of the SCP for the designs detailed in Table 1. An SCP constructed from piezoceramic only, with no metal shell (Case 1) has a flexing mode of very small amplitude. Attaching an elastic shell of the same thickness as the ceramic (Case 2) increases the displacement to a useable amplitude and reduces the negative-going portion of displacement. Doubling the thickness of the shell (Case 3) reduces the displacement a little, but raises the resonant frequency so that a higher source level is obtained. Shortening the length (Case 4) gives a much higher frequency but reintroduces some negative-going displacement with a drastic reduction in total displacement as expected. Reducing the thickness of the shortened length device (Case 5) reduces the operating frequency and regains the displacement, but with a deleterious portion in opposition. Note also that the maximum operating voltage will be reduced and hydrostatic stress effects increased with this thinner ceramic configuration.

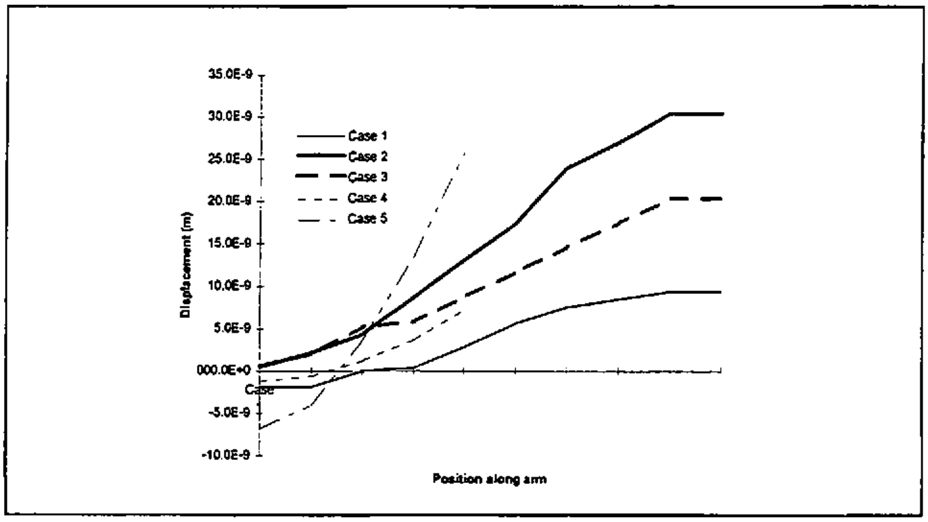

Figure 3; Comparison of displacement patterns of basic SCP designs

A possible design improvement is to add an extra layer of ceramic, inside the SCP, opposite the slot, to modify the flexing mode. The modelling results for a tapered SCP design, including designs with the additional ceramic layer are given in Table 2.

Model	Res. Freq	TVR @ res	TVR @ 100 Hz	Displ @ 100 Hz
Case 6: 6mm ceramic, small taper in shell	466	115.5	70.3	1.2E-7
Case 7: 6mm ceramic, large taper in shell	558	117.6	69	1.1E-7
Case 8: 6mm ceramic, large taper in shell, additional bimorph ceramic	799	112.2	56.3	2.0E-8
Case 9: 6mm ceramic, large taper in shell, additional opposed polarity ceramic	797	119.5	64.7	6.4E-8

Table 2; Results for tapered and additional ceramic SCP configurations

It can be seen that the principal effect of an additional ceramic layer is to increase the resonant frequency, so that a similar displacement gives enhanced power output. It can be considered as an extra stiffness, but one which does not oppose the bending moment set up between the principal ceramic and elastic shell. Connecting the additional ceramic layer with incorrect polarity gives a badly degraded displacement pattern and so poor acoustic performance.

Figure 4 compares the displacement at various positions along the arm of the SCP for the designs detailed in Table 2. The baseline design of 6mm ceramic and 6mm shell with no taper or additional ceramic is shown for comparison (Case 2). Case 6 indicates a taper of 2mm, with no additional ceramic. Case 7 is for a taper of 4mm, with no additional ceramic. Case 8 indicates a 4mm taper with additional ceramic with bimorph connection to the principal ceramic layer. Case 9 refers to a 4mm taper with additional ceramic with opposed polarity connection.

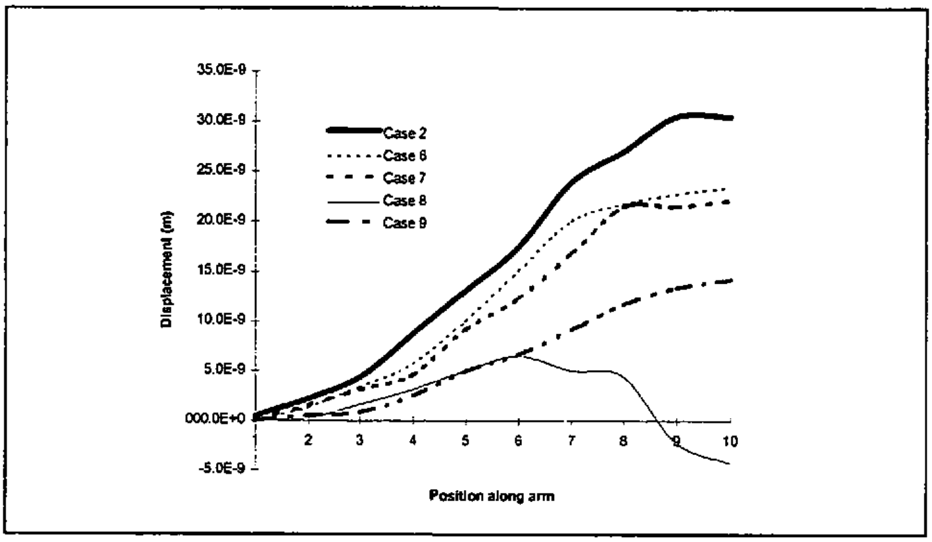

Figure 4; Comparison of tapered SCP and additional ceramic conditions

6. DISCUSSIONS AND CONCLUSIONS

Cutting a slot along the axial length of a cylindrical tube piezoceramic transducer alters the stiffness drastically and results in a low frequency transducer of miniature dimensions. Using common inexpensive materials for the ceramic and shell results in a resonant frequency well below the design aim from a device with dimensions of 114mm. Power output is therefore restricted by the limited volume displacement which can be generated. The TVR available from this size device at the frequencies natural to such a size is very limited. However, that does not mean that a much larger SCP could not be designed to operate in the frequency band and give much greater power, which would still be small compared to a wavelength.

The resonant frequency can be increased by tapering the shell. Attaching an extra layer of opposing polarity ceramic can also increase frequency and hence power output, but this needs to be connected in the correct polarity to avoid a drastic decrease in volume displacement.

In a real transducer design case it would also be necessary to consider hydrostatic and dynamic stresses. Although these could be analysed using FE techniques, they have not been studied here, as the principal aim has been to understand the radiation physics. It may be that the better acoustic designs generate stresses that are unacceptably high.

The optimum design using the materials and size constraints stated indicates a resonant frequency of 797Hz and a TVR of 119.5dB re 1μPa/V @ 1m at that frequency. This is using a 6mm ceramic of full length (minimum slot size) with a large taper on the shell and an extra layer of ceramic connected with opposed polarity. At a drive level of 2kV, appropriate to that thickness of ceramic, a source level of 185.5dB re 1μPa @ 1m could be expected. This may seem low, but it is the output of a very small device.

7. REFERENCES

[1] PAFEC Ltd. "PAFEC-FE Level 8 Data Preparation Manual. 1994

[2] Kinsler and Frey. "Fundamentals of Acoustics 2nd Edition". 1962, Wiley

[3] A B Gallaher. "Performance prediction of an array of free flooding ring transducers". Proc. IOA Vol. 17 Pt. 3, 1995