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FLEXTENTIONAL TRANSDUCERS WITH UNLIMITED DEPTH CAPABILITY

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1. INTRODUCTION

In recent years the flextensional transducer has been widely studied as a means of obtaining high acoustic powers underwater in the decade centred on 1kHz. It has the advantage of low weight and wide bandwidth compared to the alternative resonant transducer technologies but in its conventional form it has limited depth capability.

This limitation was certainly recognised as long ago as 1963 when Toulis (1,2) patented both the conventional flextensional transducer and a fluid filled version for deep immersion. However, this and more recent techniques still imposed limitations on ultimate depth and often resulted in resonant frequencies which changed with depth. This paper describes a method of free flooding the transducer while retaining its radiating characteristics in order to obtain performance which is depth invariant and unlimited, and also describes early measurements on an experimental model.

2. DEPTH LIMITATIONS

The depth performance of conventional gas-filled flextensionals is limited principally by stresses induced on the major and minor axes of the shell by hydrostatic pressure. Greater depth can be obtained by use of thicker shell walls but this requires a larger transducer for a given resonant frequency. Performance then becomes limited by the maximum size a transducer can be built while still remaining small compared to wavelength. Use of a stronger shell material may increase depth performance but eventually depth is limited by the range of stresses on the ceramic stack inducing non-linearity (3). The maximum depth obtainable by conventional technology is in the region 400-600m.

Use of flooding bladders which expand as hydrostatic pressure is increased, thus pressurising the internal gas volume by compression have been tried (4,5,6) but these still limit the depth of (thin-walled) transducers to typically 300-500m. Reference 5 also demonstrates that resonant frequency alters significantly with depth.

Other techniques (6) include the use of gas pressurisation systems but these are found in practice to have similar depth limitations.

Toulis' fluid-filled device (2) maintains the cavity compliance by the use of sealed compliant tubes. Eventual collapse of the tubes limits the depth of this type of transducer to about 1500m.

The principle of the work reported here is to produce a flextensional transducer with no depth limitation. This means that the internal cavity must be entirely filled with fluid. If the element were left entirely un-enclosed, the radiation from the inner surfaces would completely cancel that from the outer faces.

Such cancellation can be overcome by the use of a Helmholtz resonator (8,7) but the cavity size defined by a flextensional shell is too stiff to obtain good coupling. A subsidiary cavity causes a second resonance to occur and this is found to be more suitable in the frequency range of interest.

3. THEORY

The solid lines in figure 1 show a simplified equivalent circuit for a flextensional transducer in which only the quadrupole mode is represented. Component values are given by Butler (10) who includes higher modes of vibration for more detailed analysis.

Co	-	Clamped capacitance
Cd	-	Combined compliance of stack and shell
Md	-	Combined mass of stack, shell and radiation reactance
Rr	-	Radiation resistance
TEA	-	Electrical to acoustic turns ratio

Consider the same transducer with the ceramic stack suitably insulated and a hole in the top plate to allow free-flooding. The transducer now has a Helmholtz resonance. Operation can be analysed using the same circuit to which the following components are added as dashed lines.

Cc	-	Compliance of flooded cavity
Mc	-	Hole inertance
Rc	-	Hole resistance

For high output power at the Helmholtz resonance Woollett (8) has shown that the cavity compliance Cc must be large compared with Cd, but the elliptical shape of a flextensional shell always makes Cd > Cc. At resonance the water simply oscillates back and forth from inside to outside the shell with almost no net volume displacement. Referring to figure 1, the volume velocity through Mc and Rc is large compared with that through Cc and Rr.

Therefore a technique is required to reduce the internal impedance while still allowing the device to free-flood. Consider the pair of cavities in figure 2. If all dimensions are small relative to the wavelength then there is a series resonance at which the input impedance is very low, followed by a parallel resonance which has high impedance. Such a pair of resonant cavities offers a possible solution for reduction of internal impedance at certain frequencies. Figure 3 shows the application to a flextensional transducer. The shell forms the upper cavity. The lower cavity is empty and when free-flooded has compliance Cb. A hole of invertance Mb, and resistance Rb, connects the two cavities and the full equivalent circuit is a combination of figures 1 and 2.

The Helmholtz resonance now occurs at a lower frequency because the total internal volume has increased. For practical cavity volumes Cd is still greater than Cc + Cb and also the radiation resistance is reduced at lower frequencies. Therefore output power at the Holmholtz frequency is still too low to be useful. However, there is now a second resonance. It is a series resonance of Cb and Mb, modified by the shell components Cd and Md. This resonance is of great interest as it occurs at a useful frequency and radiates significant power.

A simple analysis of the equivalent circuit leads to some important observations regarding the second resonance.

(a) The volume velocity through the top hole (Mc and Rc) is negligible at the second resonance. This hole can therefore be closed and the transducer filled with any suitable liquid.

(b) The lower cavity must be made as large as possible. However it must act as a pure compliance so all internal dimensions must be less than $\lambda/4$.

(c) The walls of the lower cavity must be made as rigid as possible so that it radiates no energy from its outer surface.

A sphere is the ideal shape for the lower cavity as it has large volume and rigid walls. To satisfy condition (b) above let the sphere have radius $r = \lambda/10$ and use a liquid with velocity c and density ρ.

Volume of sphere	$V = 4/3\ \pi r^3$
Compliance of cavity	$Cb = V/\rho c^2$
For operation at frequency f	$Cb = \frac{4\pi}{3000 f^3} \cdot \frac{c}{\rho}$

Therefore at a specified frequency the maximum available compliance is determined by the ratio c/ρ for the liquid. Some possible choices are listed in table 1.

	ρ	c	ρc^2	c/ρ
	Kg/m^3	m/s	$10^9 N/m^2$	m^4/Kgs
Ethanol Amide	1018	1724	3.02	1.69
Kerosene	810	1324	1.42	1.63
Ethanol	790	1207	1.15	1.52
Sea Water	1025	1531	2.40	1.49
Methanol	791	1103	0.96	1.39
Ethyl Ether	713	985	0.69	1.38
Polydimethyl Siloxane	970	1000	0.97	1.03

TABLE 1

It can be seen that the most 'compressible' liquids are not necessarily the most suitable as they usually have low sound velocity, hence short wavelength. No commonly available liquid has c/ρ significantly higher than water. A simple free-flooding device is therefore optimum in terms of compliance and ease of construction.

Having shown theoretically that two resonances should occur it was decided to build a simple prototype to verify that those resonances could be observed in practice.

4. DESIGN AND MEASUREMENT

The design was based on the existing BAe 800Hz flextensional transducer. A single stack was used with a polyurathane encapsulating layer. Figure 4 shows the Helmholtz resonances obtained around 500Hz by free-flooding this single cavity. There was a hole of fixed size in the bottom plate and a variable hole in the top plate. Increasing hole size gave higher resonant frequency as predicted. A hydrophone placed a few metres away confirmed that very little sound was radiated.

To place the second resonance at the required frequency of 800Hz a spherical lower cavity with ideal radius 187mm and volume 28 litres was required. This was considered too expensive for initial trials. A freely available empty 800Hz flextensional shell was used instead. Its volume was only 8 litres, too small for optimum performance but adequate to test the theory. Internal supports and rigid end plates were welded to the shell for maximum stiffness, condition (c) above. It was bolted to the transducer to form the lower cavity. Conductance is shown in figure 5.

As expected the Helmholtz resonance occurred at a lower frequency, around 300Hz, and was controlled by the size of the top hole. At 800Hz the second resonance was clearly observed and showed no variation in frequency or conductance for different sized top holes. This agrees with condition (a) above. Hydrophones were used to measure both cavity pressures as functions of frequency. Results were exactly as predicted by the equivalent circuit of figure 3 (where pressures correspond to voltages across Cc and Cb) confirming the validity of the circuit.

The conductance plots show that both resonances were heavily damped. The main sources of damping were viscosity in the cavities and holes, and absorption of sound by the polyurethane. In figure 3 these effects contribute to Rc and Rb which have to be measured rather than calculated. It is known that viscous losses decrease as cavity size increases (8,9) so a full-sized lower cavity of 28 litres is expected to show higher Q, higher conductance and higher output power. Alternative materials for encapsulating the ceramic stack are also under investigation.

5. CONCLUSION

The experimental transducer has proved that sound can be generated at low frequency from a free-flooded flextensional shell with an additional cavity. Its two resonances show close agreement with theoretical predictions derived from a simple equivalent circuit. However, internal losses are difficult to predict. They are the main limitation of this kind of transducer and construction of a full-sized lower cavity is necessary for detailed studies of resistance. So far the transducer has only been tested in shallow water but since no component is sensitive to pressure it is expected that performance will be unchanged when operating at great depth.

There is a possibility of filling both cavities with a benign fluid or an acoustically more favourable fluid than water but this would lead to the need for a balancing system to allow for differentials in thermal or pressure coefficients of expansion. Seawater flooding does away with this need, indeed the need for any seals, and also minimises the on-deck weight but it means that great care has to be taken to protect all surfaces from attach by seawater at great pressures. However, this problem has been solved for other types of transducer and is not a limitation.

The technique described here is thus seen as the first step in creating a new generation of flextensional transducers with enhanced performance for the 1990's.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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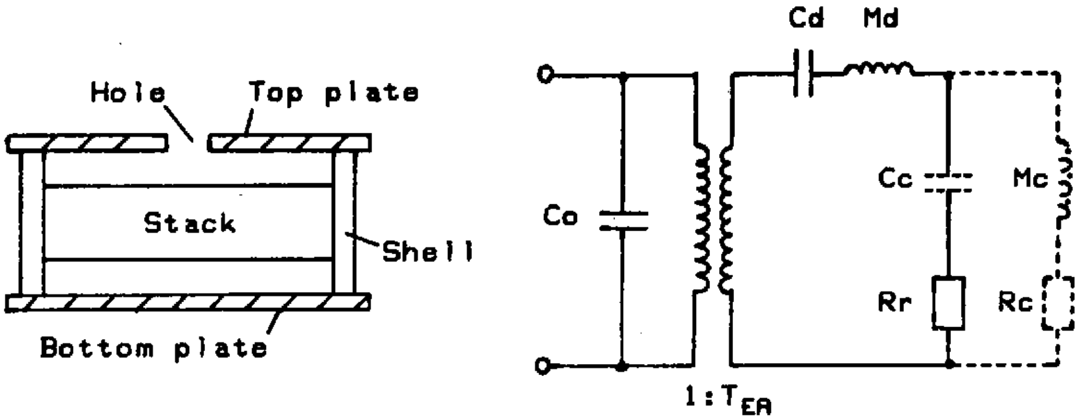

FIGURE 1 Free flooded flextensional transducer.

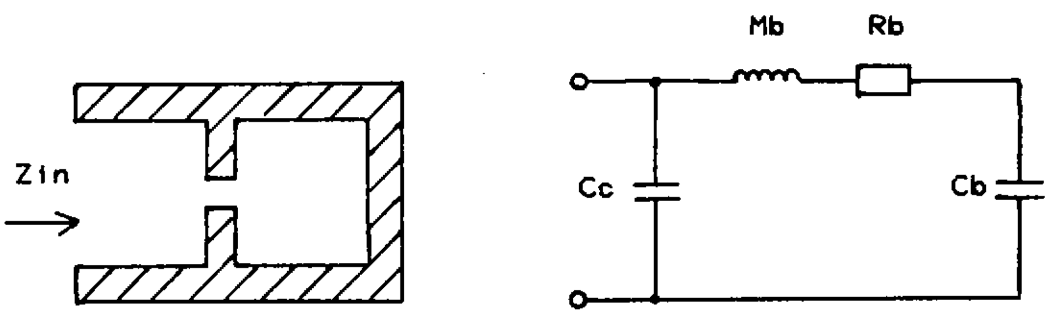

FIGURE 2 Two cavities with acoustic equivalent circuit.

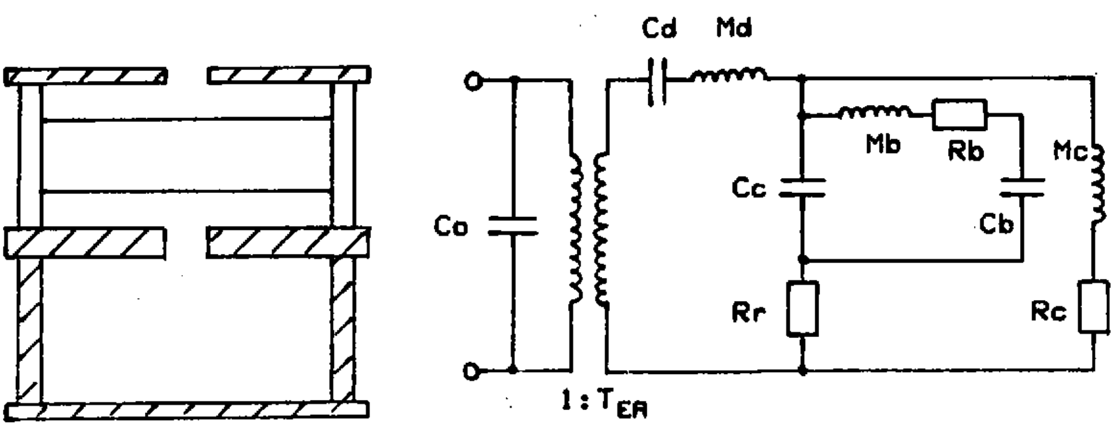

FIGURE 3 Flextensional transducer with second cavity.

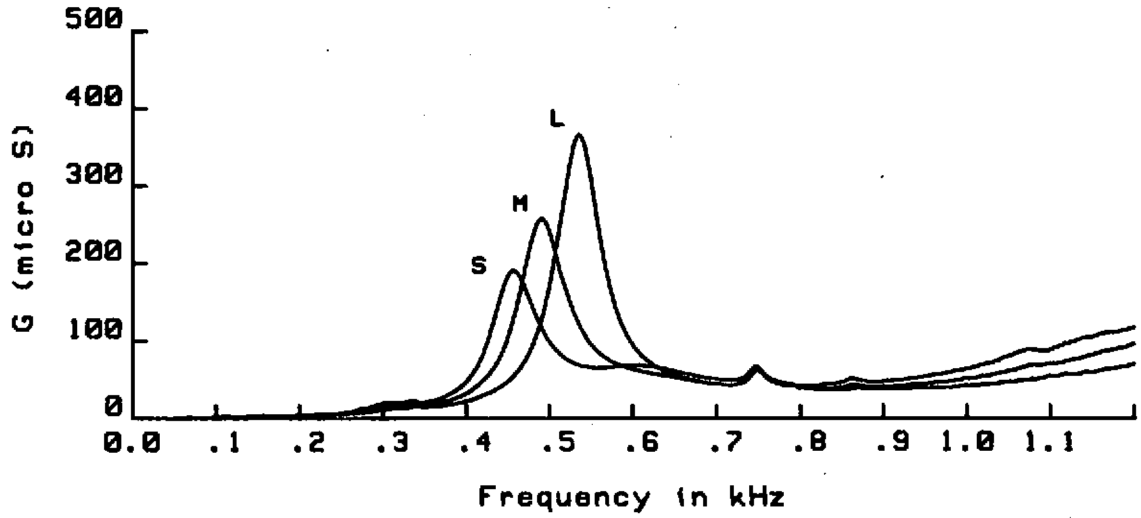

FIGURE 4 Free flooded flextensional transducer.

Top hole: L - Large M - Medium S - Small

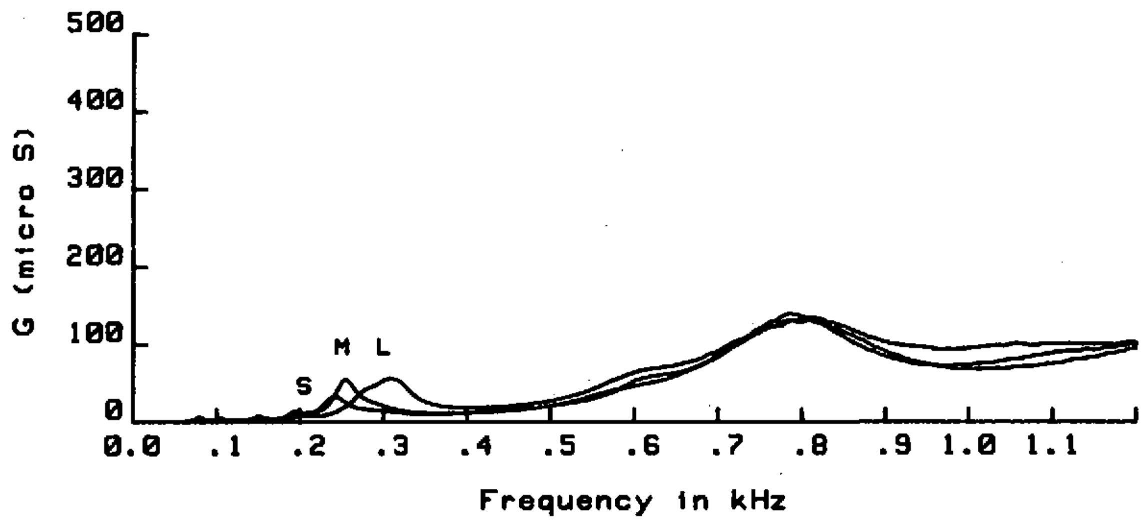

FIGURE 5 Flextensional transducer with second cavity.