

DESIGN LIMITATIONS OF ALUMINIUM SHELL,
CLASS IV FLEXTENSIONAL TRANSDUCERS

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1. INTRODUCTION

The flextensional transducer was patented in the United States in 1963 (References 1 and 2). Work in more recent years (References 3 and 4) has shown the capability of the device for generating sound in the frequency regime around 1 kHz. The particular advantages of the flextensional transducer are the wide bandwidth (Q is typically 3) and high efficiency (typically 60%) which can be obtained from its compact size and relatively low mass. It is small compared with the wavelength it emits so its far-field polar pattern is approximately omnidirectional.

Reference 3 details four classes of flextensional transducers. Of these, Class IV poses the least engineering problems and has been pursued the furthest. It takes the form of an elliptical cylinder. An extra advantage of this class is that a number of devices may be assembled into a continuous stave, allowing control of beam pattern in one plane.

Figure 1 is a general sketch of a Class IV flextensional transducer and details the variables. It will be seen that there are many variables which may affect the performance; the purpose of this paper is to explore the effect of these and to discover some limits.

Mathematical analysis of the flextensional transducer is difficult (see, for instance, Reference 5) so a mechanical model of the transducer has been made and subjected to finite element analysis using BAE proprietary software on a desk top computer. The analysis is not sufficiently rigorous to permit practical design work without reference to a detailed analysis using NASTRAN, but it does yield approximate answers in a few minutes. This analysis technique is also sufficient for comparative studies and has been used extensively in preparing this paper.

Although materials other than aluminium may be used for the shell (see References 4 and 6), all work at BAE has used aluminium, so this paper restricts itself to the one shell material.

2. VARIABLES

The variables are shown in Figure 1; the principal variables are the major axis, $2a$, the ratio of major to minor axes, a/b , and the wall thickness, t . It should be noted that the external dimensions are $2a+t$ and $2b+t$. It is assumed that motion is uniform throughout the depth, d , of the shell.

In terms of resonant frequency the dimensions of the ceramic stack are of secondary importance, but they greatly affect the power available, particularly at higher frequencies, as they specify the volume of ceramic. It should be noted that the ceramic width, w , limits the ceramic volume for a given size of shell as it limits the ceramic length, l , (this will be apparent from Figure 1) and the ceramic depth D is limited to about 80% of the shell depth d to allow space for electrodes and connections.

Figure 2 shows the in-water resonant frequency variation for differing wall thicknesses for a given ratio of major/minor axes. Figure 3 shows how resonant frequency varies with semi-major axis and major/minor ratio for a given shell thickness. Resonant frequencies in both air and water are shown. It will be seen that considerable mass loading occurs in water. These frequencies have been calculated for a constant thickness, t , of 15 mm.

3. TRANSDUCER MECHANICS

Existing ceramic materials such as Lead Zirconate Titanate may generate substantial forces but they are limited as a means of generating acoustic radiation at low frequencies as they cannot provide the required volume displacement. It is possible to employ resonances of radial or flexural mode, but these have low coupling coefficients, leading to narrow bandwidth and limited power handling. In the flextensional transducer, the ceramic operates in "33" mode which optimises coupling coefficient while the shell provides a lever mechanism to generate a large displacement.

The transducer operates by altering the length of the major axis, thereby causing a magnified change in the minor axis. Although the displacement volumes of major and minor axis are of opposite phase the net volume displacement is large, resulting in high acoustic power output. However, the effect of hydrostatic pressure is to squash the ellipse in its minor axis and elongate the major axis, and this subjects the ceramic stack to tensile forces. Therefore, compromise between operating power and operating depth is a significant limitation in the design of this type of transducer.

The ceramic is prestressed to obviate tensile stress at maximum depth and peak amplitude. This is done by designing an interference fit between stack and shell such that there is a high residual stress in the shell and stack.

The compromise between output power and operating depth may be quantified in terms of the maximum stress generated in the shell. The optimum performance will therefore be obtained using stronger aluminium alloys, although it should be noted that N8(5083) alloy, which has the best resistance to marine corrosion has limited strength. Use of stronger aluminium alloys creates extra design problems in protection from corrosion.

As the transducer is small compared to the wavelength it emits, its radiated acoustic power may be approximated to that of a point source in terms of volume displacement.

$$\text{The equation Power} = \frac{\rho c k^2}{8\pi} Q_s^2 \quad (1)$$

(Where Q_s = RMS Volume displacement rate and k = wavenumber)
derived from Reference 7 may be re-written as

$$\text{Power} = \frac{2\pi^3}{c} \rho f^4 (\text{Vol}_{o\text{-peak}})^2 \quad (2)$$

This equation has been used to calculate the power output obtained from a given end extension (i.e. increase in semi-major axis).

It has been noted from Figure 3 that there is a large difference between resonant frequency in air and in water. A formula for mass loading of

$$M = ab^2 \rho \propto \beta k \quad (3)$$

where β and k vary as a and b and α is mode shape dependent, has been derived from Reference 8. Experience has shown it to be of the correct order, but it should be noted that equation 2 has an f^4 term. This means that a small error in in-water resonant frequency will result in a large error in power output. However, the figures used in this paper are suitable for comparative purposes.

4. LIMITATIONS

Figures 2 and 3 would appear to show that low frequency devices can be made by using a suitably large major axis and a thin shell wall. However, such devices would be extremely weak. It has already been stated that power output has to be compromised with operating depth to maintain the shell stress within its material limit, and the effect is found to be more severe at low frequencies. This is illustrated in Figure 4. Increasing the thickness of the shell gives better depth capability but at higher frequencies. It also increases the force needed to compress the shell to insert the stack. It should also be noted from equation 2 that the power is reduced drastically as the frequency is decreased; maximum acoustic power is only about 10W at maximum operating depth for the 300-400 Hz devices of 100 mm shell depth.

Table 1 summarises the performance of a large flextensional design using Aluminium N8(5083). Again stronger aluminium alloys could be used to increase depth or power output, but corrosion protection would be needed and the compressing forces would also be increased.

Better performance may also be obtained either by use of pressure compensation methods, or by using a glass composite material (see References 4 and 6). This last gives rise to a more compact transducer, so that hydrostatic pressure exerts less tensile force on the stack.

TABLE 1

PERFORMANCE LIMITS OF A LARGE TRANSDUCERSemi-major axis 300 mm, Semi-minor axis 100 mm

SHELL THICKNESS	15 mm	25 mm	35 mm
Resonant Frequency	296 Hz	395 Hz	465 Hz
Maximum Depth	16m	46m	92m
Acoustic power at maximum depth (100 mm shell depth)	8W	10W	14W
Compressing Force for 100 mm shell depth	56 kg	315 kg	1340 kg
Compressing force if shell depth adequate for 100W	200 kg	1000 kg	3600 kg

The indications from Figure 4 and Table 1 are that 500 Hz and 100m operating depth represent the approximate lower frequency design limits of the Class IV flextensional transducer using an aluminium N8 shell.

At higher frequencies a smaller, stiffer shell is required, so depth capabilities of typically 200m and power outputs in excess of 1 kW are possible. However, there are limiting factors.

The small shell size and high power output may lead to cavitation conditions, and a 3 kHz device may typically require an operating depth of 50-100m to generate full power without cavitation.

The more serious limitation in smaller devices is the achievable electrical power input. The power handling capability of a volume V of ceramic may be derived from Reference 9 as

$$\text{Power} = 2\pi f Q_m k^2 \epsilon_0 \epsilon_r E^2 V \quad (4)$$

where k = coupling coefficient $\epsilon_0 \epsilon_r$ = permittivity and E = Electric field strength.

As the volume of the transducer is reduced, so is the volume of ceramic which can be used. The value of k is found in practice to be approximately .25, and this may mean that the power handling capability of the shell can only be reached by using very high electric fields.

Although heating effects should be considered, the $\tan \delta$ losses are found to be relatively low providing suitable ceramic is used, and high frequency devices provide a relatively short path to a good heat sink, so thermal limitations are not normally important.

Performance limitations are summarised in Figure 5. Rough calculations show that the maximum volume displacement amplitude is approximately .1% of transducer volume and an approximate volume can be derived for any operating frequency. It is also found that the ceramic can only occupy a maximum of about 25% of the transducer volume. Figure 5 demonstrates how the power output capability of the shell rises dramatically with frequency (as does the power density and therefore the likelihood of cavitation) whereas the electrical power handling falls gently for a given operating field.

It will be seen that whereas up to about 800 Hz the device is volume displacement limited, the electrical input is the high frequency limitation and the mechanical performance capabilities can only be realised by using very high electric fields.

An upper frequency limit of 3 to 4 kHz is also imposed in practice by the small size of the device giving rise to difficulties in machining and assembly.

5. CONCLUSIONS

The Class IV flextensional transducer is an efficient wide band miniature device with moderate depth capability in the frequency regime around 1 kHz.

Mathematical analysis is difficult, and is further complicated by the large number of variables. However, it has been possible to construct a finite element model which allows rapid analysis.

Using this model it has been shown how resonant frequency varies with the important dimensions major axis, ratio of major to minor axis and wall thickness.

Stress in the aluminium shell is a limitation in power output and operating depth. Improved performance can be obtained by using stronger alloys, although problems will arise from corrosion. At low frequencies the stress build-up is mainly due to hydrostatic pressure, so that operating depth becomes very limited, even at very low output powers.

At high frequencies depth limitation is less important, but power output is limited by the volume of ceramic which can be installed, and cavitation is possible at low operating depths. Powers of the order of 1 kW are possible from devices of maximum dimension 170 mm.

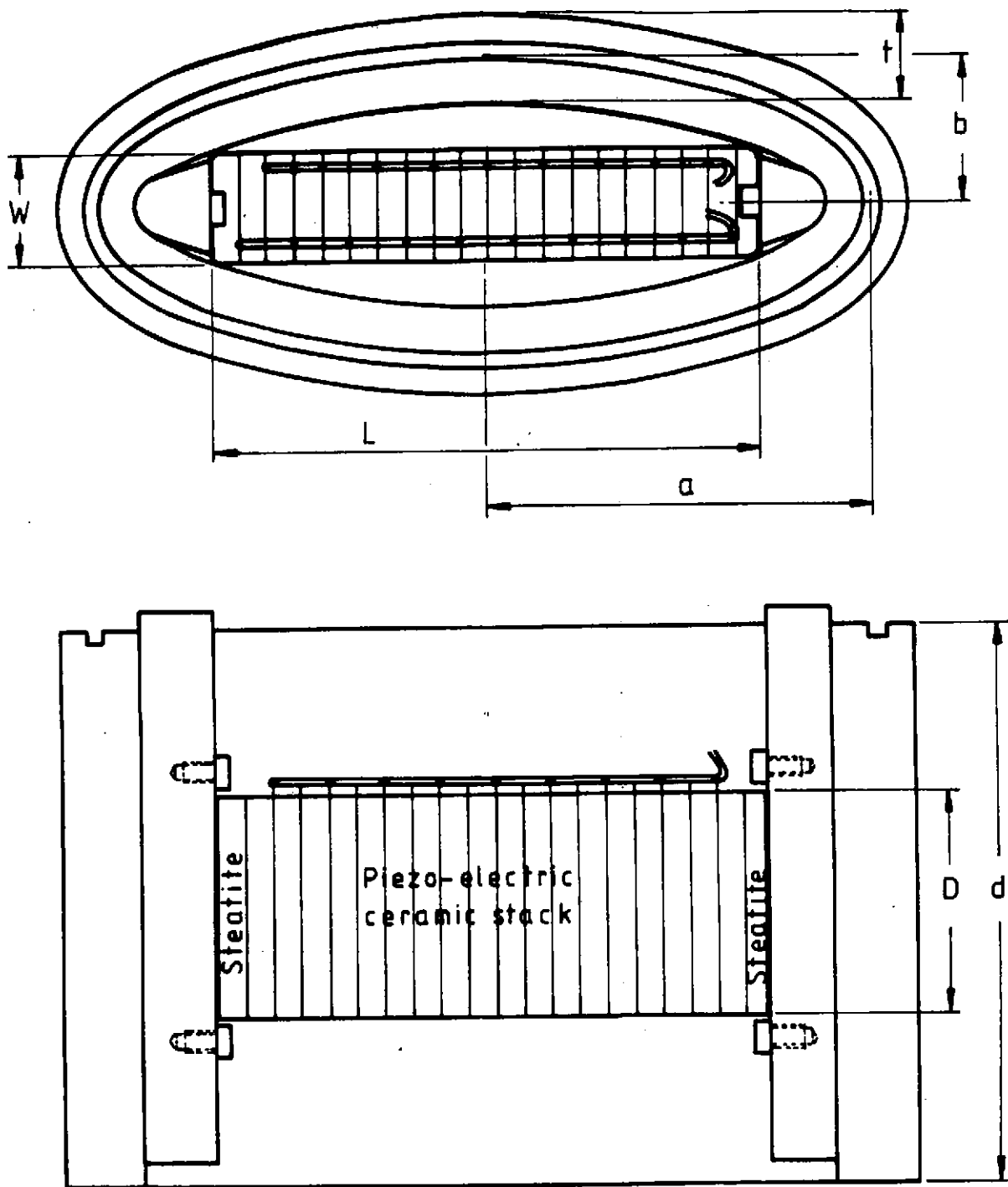
The useable frequency range of aluminium shell Class IV flextensional transducers has been shown to be approximately 500 Hz to 3 kHz.

6. REFERENCES

- (1) J. Toulis US Patent 3,277,433, (1963).
- (2) J. Toulis US Patent 3,274,537, (1963).
- (3) Pagliarini and White : Small, Wide Band, Low-Frequency, High-Power Sound Source Utilizing the Flexensional Transducer Concept. IEEE Oceans 1978, P333.
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- (9) Berincourt, Curran and Jaffe : Piezoelectric and Piezomagnetic Materials and their function in Transducers, in Mason, Physical Acoustics Volume 1A, Academic Press.

7. FIGURES

- FIGURE 1 : Class IV flexensional transducer. General layout and variables.
- FIGURE 2 : Variation of resonant frequency with semi-major axis and wall thickness in water.
- FIGURE 3 : Variation of resonant frequency with semi-major axis and ratio of major to minor axis. Air and water.
- FIGURE 4 : Variation of depth limitation with semi-major axis, wall thickness and frequency.
- FIGURE 5 : Frequency limitations due to volume displacement, cavitation and electrical power handling.



CLASS IV FLEXTENSIONAL TRANSDUCER
GENERAL LAYOUT AND VARIABLES

FIG.1

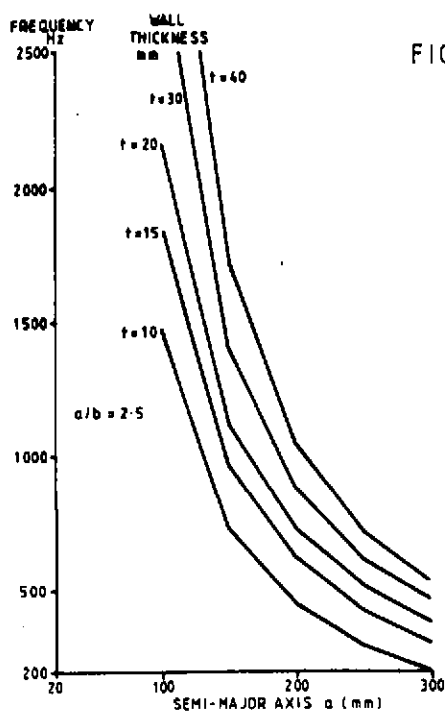


FIG. 2

VARIATION OF RESONANT FREQUENCY
IN WATER WITH SEMI-MAJOR AXIS
AND WALL THICKNESS

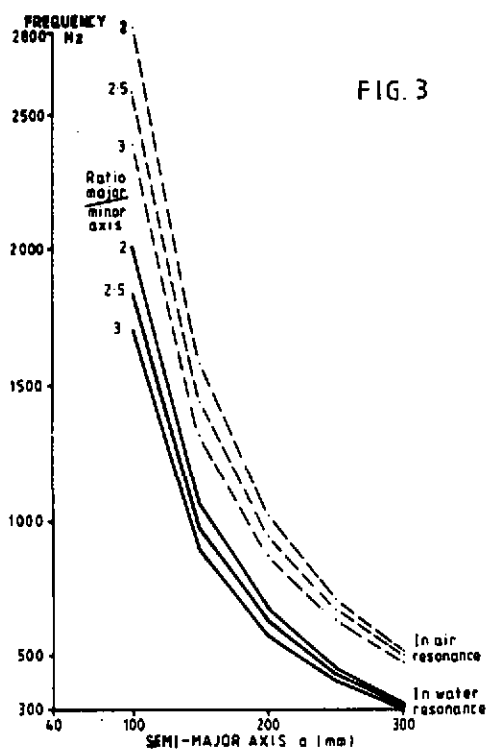


FIG. 3

VARIATION OF RESONANT FREQUENCY
WITH SEMI-MAJOR AXIS AND RATIO
OF MAJOR TO MINOR AXIS AIR & WATER

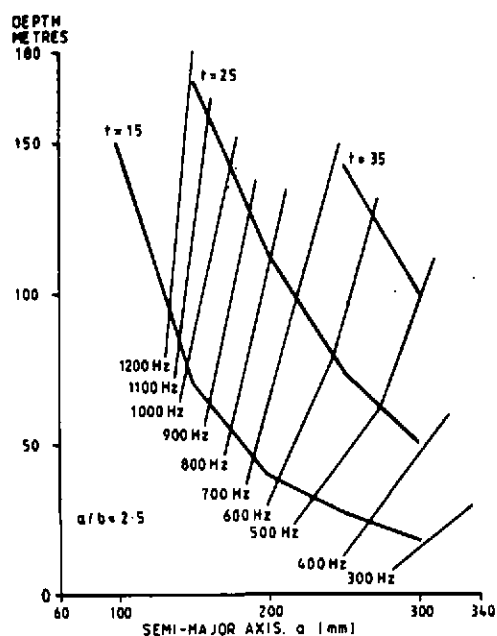


FIG. 4

VARIATION OF DEPTH LIMITATION WITH
SEMI-MAJOR AXIS, WALL THICKNESS AND
FREQUENCY.

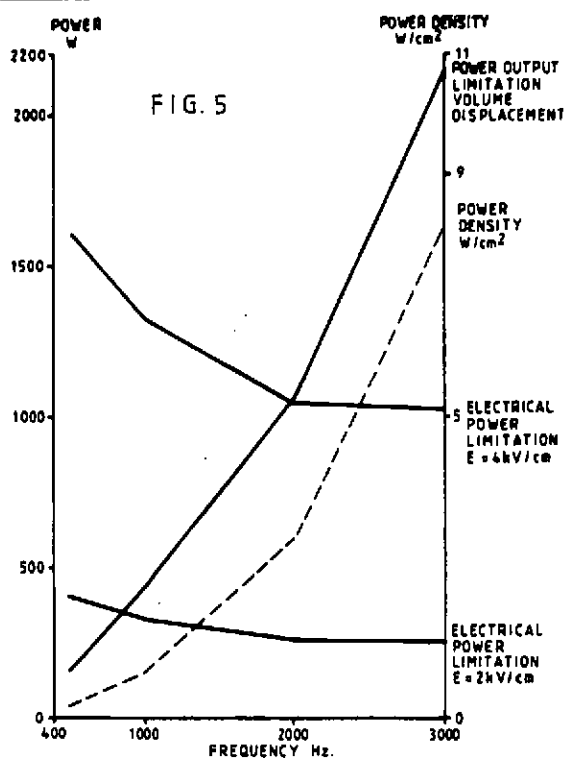


FIG. 5

FREQUENCY LIMITATIONS DUE TO VOLUME
DISPLACEMENT, CAVITATION & ELECTRICAL
POWER HANDLING 100min SHELL DEPTH