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MAGNETOSTRICTION IN FLEXTENSIONAL TRANSDUCERS

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INTRODUCTION

The advantages of flextensional transducers as efficient miniature wideband low frequency sources have been discussed elsewhere [1]. However, there are limited advantages in miniaturising the transducer if savings cannot also be made in the other power components.

Reference [1] showed the resonant frequency of a flextensional transducer to depend pricipally on the major and minor axes, shell wall thickness and shell material properties, these dimensions being illustrated in Figure 1. For a given maximum dimension, it is possible to reduce the resonant frequency either by reducing the wall thickness or by changing the shell material.

It should be noted, however, that apart from any mechanical consequences, the electrical problems induced by this frequency reduction in a ceramic - driven flextensional transducer are severe. This is illustrated in Table 1, using figures derived from experimentation on a standard 3 kHz flextensional transducer design.

PERFORMANCE COMPARISON

Column 1 of Table 1 shows performance data for the standard transducer, column 2 shows the performance obtained from a glass reinforced plastic (GRP) replica of this transducer while column 3 indicates the performance required of an ideal magnetostrictively driven version of the GRP transducer. The ideal magnetostrictive element is assumed to provide the same power output for the same VA input.

For the purposes of comparison a source level of 194 dB re 1μ Pa @ 1m (nominally 200W acoustic) is specified. The transducer has a major axis of 75 mm, a minor axis of 28 mm and a wall thickness of 16 mm, giving external dimensions of 166 mm by 72 mm. The shell depth is 100 mm.

It is also assumed that a transistor power amplifier of low output impedance is used.

It will be seen that considerable weight could be saved in matching components even in this low power example by use of a magnetostrictive drive. It must be noted, however, that in a magnetostrictive system, VA not converted into acoustic power will mainly be dissipated in ohmic losses rather than stored capacitatively.

MECHANICAL REQUIREMENTS OF MAGNETOSTRICTIVE MATERIALS

Magnetostrictive materials operate on a square law (unlike ceramics) so it is necessary to provide a bias field in order to obtain linear performance, as illustrated in Figure 2. Magnetostriction may be either positive (material expands on application of field) or negative (material contracts on application of field).

Table 1. Comparative performances of flextensional transducers

	Aluminium Shell Transducer	GRP Replica	GRP Ideal Magneto-strictive
Mass	3 kg	2.2 kg	2.2 kg
Resonant Frequency	3 kHz	1.5 kHz	1.5 kHz
Sensitivity	134 dB	125 dB	
Voltage for 194 dB	1000V	2818	(200)
G and B (μS) at resonance	290, 1270	46, 579	
Efficiency %	60	50	
VA in for 200W acoustic	1303	4612	4612
Matching unit size (mm)	120 dia x 50	130 dia x 80	54 x 27 x 32 (capacitor)
Matching unit weight (kg)	3 kg	6.5 kg	0.25 kg

Another essential difference is that saturation strains in the material are set by mechanical rather than electrical limitations. There is thus a mechanical limitation on the power output available from a magnetostrictive drive. The effect of saturation strain on power capability is illustrated in Table 2. For comparison, ceramic drives provide strains, usually limited by electrical factors, of about 200 parts per million zero-to-peak.

Table 2. Effect on power output of saturation strain

Power Output, Watts		
Axes, mm a*b*t*depth	Transducer 1 100*40*20*100	Transducer 2 200*80*30*200
Shell material	FRP	GRP
Element length	100 mm	200 mm
Frequency	800 Hz	300 Hz
Strain 10 ppm	.006W	.0064W
Strain 100 ppm	.6W	.64W
Strain 1000 ppm	60W	64W

It is also important to consider the strength of the material: stresses will not only be set up by the transducer operation but also by the effect of hydrostatic pressure on the transducer. If the cross section area of the magnetostrictive drive is small then the forces exerted by hydrostatic pressure will be relatively greater. Either the magnetostrictive material must be stronger than ceramics or depth performance will be limited.

The ideal material will have a large tensile strength so that the transducer shell does not have to be prestressed to keep the driver in compression. This may not be available in practice.

ELECTRICAL PROPERTIES OF MAGNETOSTRICTIVE MATERIALS

Magnetostrictive materials are driven by current rather than by voltage. This makes them more suitable for driving by modern amplifiers by presents greater scope for resistive losses to occur. The causes of resistive loss must be considered.

The first, and most obvious cause of ohmic loss is in the energising coils. For instance, if a field of 1000 amp/metre set up in a 50 mm long coil, outer diameter 17 mm, inner diameter 13 mm will have a loss of 1.6W, as:

$$\text{Power Loss} = F^2 \, l^2 \, \rho P/AS \qquad (1)$$

where F = field strength (in amp/metre)
l = coil length
P = mean coil circumference
A = coil cross section
S = wire packing density
ρ = wire material resistivity

Ideally, the magnetostrictive material should have a high relative permeability so that a high flux density (and therefore power input) can be obtained from minimum magnetising field.

Alternating fields will set up eddy currents in the magnetic materials, both in the magnetostrictive elements and in any pole pieces which may be used to complete a magnetic circuit. Eddy current losses are calculated by:

$$W_E = \frac{(\pi \, Bdf)^2}{16\alpha} \qquad (2)$$

where B = flux density, d = rod diameter,
f = frequency, α = resistivity.

Note the dependence on frequency: magnetostrictive transducers are essentially low frequency devices. The need for a material of high resistivity is also evident. Thirdly, the need for small cross section area is evident. Where a large area is needed for reasons of mechanical strength, it will be necessary to laminate the material to reduce its effective area.

Hysteresis loss is described by:

$$W_H = \underline{\Delta B.H} \text{ watts per hertz per cubic metre,} \qquad (3)$$

where ΔB.H is the area within the hysteresis loop.

This effectively describes the work done in magnetising and de-magnetising the material as the field is cycled from minimum to maximum value. Published data on hysteresis in magnetostrictive materials are obscure, but values need to be obtained to assess transducer efficiency. Note the frequency dependence.

The most important factor to consider is the conversion of the electrical energy into mechanical energy, to be dissipated as acoustic radiation. The conversion is governed by a transformation factor:

$$N_t = k^2 \ (N \ d_{33} \ A/l.S_{33}{}^h) \qquad (4)$$

where N = number of turns on coil
k = coupling coefficient of the rod
A = cross section area
l = length
d_{33} = strain coefficient
$S_{33}{}^h$ = compliance

For a given magnetising field, the amount of acoustic energy is determined by the coupling coefficient. Note, however, that in the magnetostrictive case, energy not converted into motion is dissipated in the losses described above rather than stored reactively. The importance of high coupling coefficient is therefore greater in obtaining high efficiency. Figure 3 shows the typical dependence of efficiency on coupling coefficient.

PROPERTIES OF REAL MAGNETOSTRICTIVE MATERIALS

Sections 3 and 4 above have shown the importance of saturation strain and coupling coefficient in obtaining high acoustic performance from magnetostrictive materials. The desirability of other properties has also been indicated. It is now necessary to consider those values of real magnetostrictive materials.

For the sake of simplicity, the effects of high stresses or fields on these properties will not be considered at this stage.

Traditionally, nickel was used as a magnetostrictive driver. It enabled the production of very rugged transducers, but its very limited saturation strain gave it a poor power output to weight and its low coupling coefficient limited efficiency. Alloys of nickel and cobalt have been shown [2] to have considerably higher coupling coefficient and greater resistivity but their saturation strain is not significantly increased. Both nickel and cobalt - nickel are negatively magnetostrictive.

Permendur alloys contain iron, chromium and vanadium and are positively magnetostrictive. Increased saturation strain is obtained at the expense of coupling coefficient. Tables of data on these and similar materials are to be found in [3].

In recent years a new family of materials based on the Rare Earth series of the periodic table have been prepared which possess giant magnetostrictive effects. It is not intended to discuss the crystallographic properties of the material here, [4] for instance may be consulted, but the material provides saturation strains greater than 1000 parts per million (over thirty times that of nickel) and theoretical maxima of 2500 parts per million are predicted [5]. Coupling coefficients of about 0.7 are available. The material is positively magnetostrictive.

Availability of this material has transformed the performance capabilities of magnetostriction in low frequency power generation from compact sources. Of course the material has disadvantages: it is very brittle and it is fabricated from expensive raw materials. It also has a very low rélative permeability, necessitating the use of high magnetising fields. Typical alloy composition is Terbium 0.3, Dysprosium 0.7, Iron 1.95.

Approximate comparative data, derived from the literature in general, for the various driver materials are given as a guide in Table 3.

Table 3. Comparison of magnetostrictive materials

	Nickel	Cobalt Nickel	Permendur	Rare Earth
Density kg/m3	8900	8900	8100	9100
Youngs Modulus GPa	200	190	160	30
Saturation Strain	-31	-35	+50	+1400
Coupling Coefficient	0.3	0.51	0.37	0.7
Compress. Strength	-	-	800	700 MPa
Tensile Strength	-	-	600	25 MPa
Resistivity μ ohm cm	6.7	10.5	40	60
Relative Permeability	60	80	95	5

APPLICATION TO FLEXTENSIONAL TRANSDUCERS

The preceding section has shown the superiority of Rare Earth materials for high power generation. Early work in this area has been reported in [6], but little constructional detail is given. The remainder of this paper will concentrate on these materials only, and will consider application to the 'ideal' magnetostrictive transducer described in Table 1.

Completion of a closed flux path is most easily achieved by the use of pole pieces connected across a pair of magnetostrictive elements, as illustrated in Figure 4. The pole pieces must be configured for minimum eddy currents, but must also the mechanical loads imposed by the design.

It is also important to minimise eddy currents in the Rare Earth rods while maintaining sufficient cross section area for strength. Lamination of Rare Earth rods is possible, but the brittleness of the material militates against this. Maintaining cross section area may best be achieved by clustering rods of smaller diameter together, as illustrated in Figure 5.

The need to place magnetising coils around the elements restricts their length to that within which the coils' diameter can be accommodated. Given the superior saturation strain capability of the material this does not compromise the power output. The element and coil assembly will occupy a depth of a little over two coil diameters. This makes the assembly the ideal shape to fit in the interior of the transducer of dimensions used for Table 1, and the complete transducer is illustrated in Figure 6.

Assuming material properties quoted in Table 3 and the use of 50 mm rods of 6.35 mm diameter clustered in fours, performance predictions are as given in Table 4. These were derived from proprietary BAe software.

Table 4. Performance predictions for example transducer

Voltage for 194 dB	12.6
Current for 194 dB	56
VA for 194 dB	708
Eddy current loss	91W
Coil loss	97W
Hysteresis loss	35W
Mechanical losses	112W
Efficiency	37%

It will be seen that the requirement to conserve VA is not only met, but comfortably surpassed. However, the efficiency is lower than that obtained by ceramics and thermal generation has not been considered in the above calculations. Power output may be thermally limited.

CONCLUSIONS

Flextensional transducers provide a useful means of miniaturising low frequency projectors, but a condition can be reached where the size of the matching unit exceeds that of the transducer, and no benefit is gained.

Magnetostriction allows the use of a significantly smaller matching unit, but the performance available from traditional driver materials is too limited to be worthwhile.

The advent of Rare Earth magnetostrictive materials with very high saturation strain promises to transform the performance available. The high coupling coefficient also permits good efficiency. However, the brittle nature of the material makes it more difficult to handle than traditional materials.

The materials are still in early stages of production and more work needs to be done on the characterisation of these materials.

The magnetostrictive drive configuration is well suited to flextensional transducers, and good performance capability is predicted.

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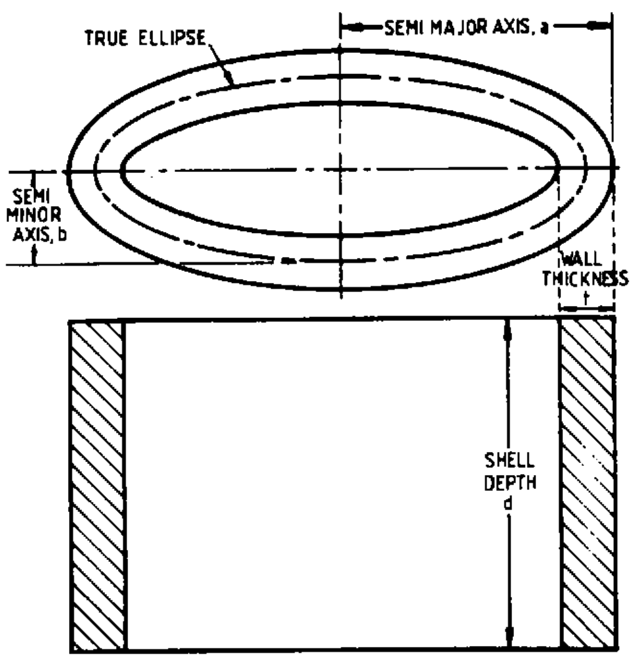

Figure 1. Flextensional Transducer Shell Dimensions

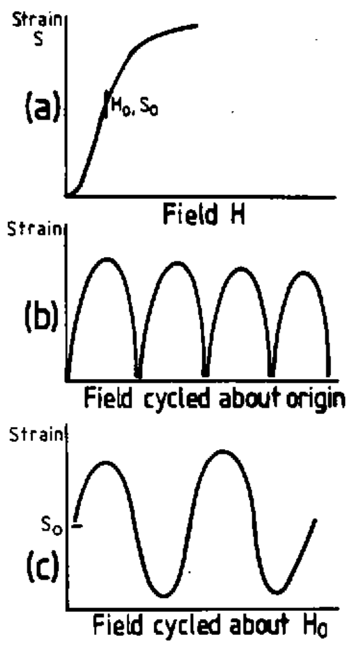

Figure 2. Use of Bias Field For Linear Drive

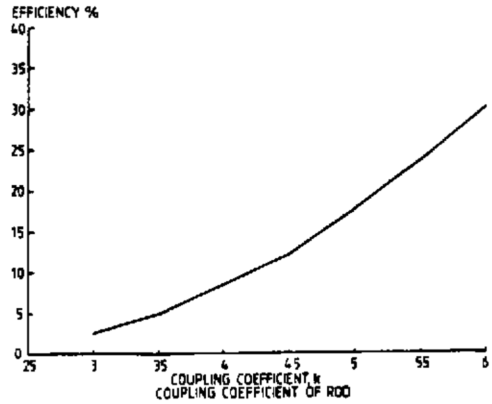

Figure 3. Typical Dependence Of Efficiency On Coupling Coefficient

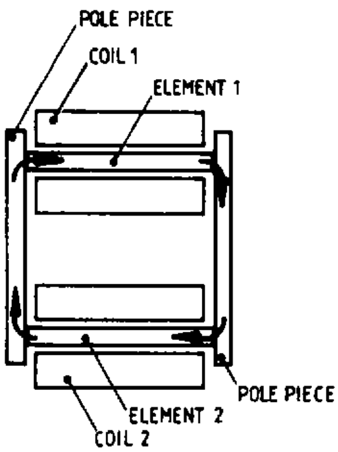

Figure 4. Arrangement Of Closed Flux Path

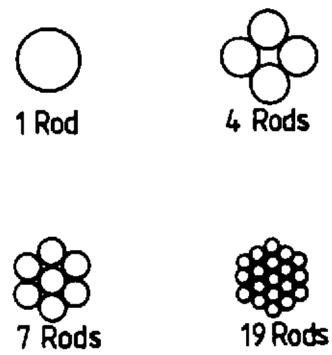

Figure 5. Clustering Of Rods Of Smaller Diameter To Reduce Eddy Current Loss

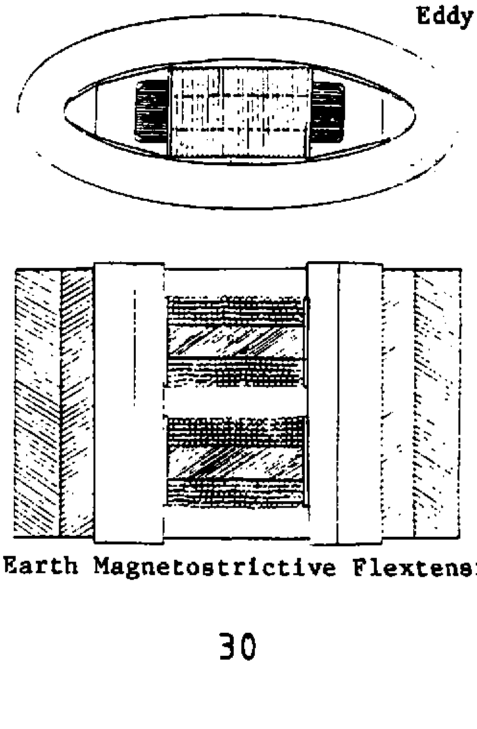

Figure 6. Rare Earth Magnetostrictive Flextensional Transducer