THE DESIGN OF SANDWICH TRANSDUCER

The sandwich transducer is a convenient means of achieving a low ultrasonic frequency (20 - 80 Kc/s) transducer using PZT ceramics and commonly available metals. As a transducer it is robust, cheap and relatively simple to construct. By using metal masses either side of the ceramic good cooling is achieved when the ceramic is operated at high power levels.

The principles behind the design are based on the work of Langevin* who produced the first sandwich transducer over forty years ago. Consider first of all the properties of a quarter wave transformer. This is a device which when placed between a generator and its load will change the effective load impedance that the generator sees by an amount depending upon the value of acoustic impedance of the transformer material and the load. The relationship is a simple one and numerically is given by: -

$$Z_e = \frac{Z_p^2}{Z_1}$$

where Z_e = effective load on generator

Z_p = acoustic impedance of transformer plate

Z_1 = " " " the load.

The acoustic impedance in each case is given by the product of density and velocity of sound (pc) of the material concerned.

The first step, therefore, is to select an intermediate plate between the crystal and the load of the required acoustic impedance. Such an arrangement on its own would be quite a suitable transducer for many purposes, but a substantial improvement can be obtained by using a rear mass on the other face of the crystal. The action of a second plate is firstly to lower the frequency at which the whole structure would be naturally resonant. Secondly if the plate is made a quarter wave thick then the rear face of the crystal is effectively clamped, providing the rear load is a mechanical short circuit, i.e. air-backed. Under these conditions the crystal will not radiate any useful energy to the rear. The effective output of the crystal is therefore directed forwards into the load through the front quarter wave plate.

The frequency at which the whole assembly will resonate depends upon the density and velocity of sound in the various sections, the thickness of each section and to a lesser extent the ratio of areas between plate and ceramic. The complete equation for a half wave resonator is based on the concept that the structure is virtually a transmission line and is as follows: -

* B.P. No.145,691

$$w_r\left(\frac{t}{c}\right)_C + \tan^{-1}\left[\frac{(pc)\ Fp}{(pc)\ C}\ \tan w_r\left(\frac{t}{c}\right)_{Fp}\right] + \tan^{-1}\left[\frac{(pc)\ Bp}{(pc)\ C}\ \tan w_r\left(\frac{t}{c}\right)_{Bp}\right] = \pi$$

where:

$\left(\frac{t}{c}\right)_C ; \left(\frac{t}{c}\right)_{Fp} ; \left(\frac{t}{c}\right)_{Bp}$ = thickness of each section divided by its sound velocity.

w_r = 2π x resonant frequency

(pc) = acoustic impedance

C = cerami se tion

Fp = Front plate

Bp = Back plate

The third most important feature to be considered is the bias bolt that runs through the whole transducer assembly. Harry Miller in U.S. Patent No.2,930,912 clearly shows the reasons why this is necessary. Suffice to say here that the basic reason lies in the fact that all piezoelectric crystals and particularly the ceramic variety such as barium titanate and PZT have a poor tensile strength. When the transducer is vibrating with high driving voltages applied the level of tensile stress reached at the nodal plane where the ceramic is positioned can be very high. The stress may in fact reach the ultimate figure for the material and cause a fracture. The bias bolt is therefore used to place the whole assembly into compression at a value equalling or just exceeding the value of tensile stress

The choice of materials for the transducer falls into three parts as follows: -

1. The piezoelectric driver material.

The designer can select from quartz, barium titanate and lead zirconate titanate. The latter, of which PZT* is an outstanding example is probably the most useful, since its conversion efficiency, temperature limits of operation and dielectric constant means that the final transducer performance is more likely to be limited by the quality of transducer construction, e.g. glued joints, than by the PZT itself. Quartz was the material used by Langevin in his original sandwich transducer. However, even in this form the electrical impedance is still high compared with a PZT transducer, and this can lead to difficulties with the high driving voltages needed.

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2. The front and rear plates.

The material for the plates is determined to a large extent by the application to which the transducer will be put. Bearing in mind the comments made previously on the need for a material with an intermediate value of (ρc) and assuming PZT is the crystal driver, the following table should assist in selection: -

Back Plate	Crystal Driver	Front Plate	Load
Brass) Steel) Magnesium)	PZT	Dural) Aluminium) Magnesium)	Water
Brass) Steel) Magnesium)	"	Magnesium) Polythene) Bakelite)	Air
Magnesium) Dural) Steel)	"	Magnesium) Dural)	Complex, e.g. ultrasonic cleaning tank

Whereas a water and air load can usually be considered an infinite medium, the problem of an ultrasonic cleaning tank impedance is more difficult to specify. It is to a large extent dependent upon the size of the tank, depth of cleaning solvent, thickness of tank bottom and spacing of transducers.

The case of driving into air is extremely difficult because of the high degree of mismatch between the PZT crystal and air. The ratio of mismatch is in the order of 500,000 : 1 but a noticeable improvement can be brought about by using a plastic front plate.

The mismatch between PZT and water is about 20 : 1. This can be easily corrected by using one of the lighter metals as a front plate. In practice one can often design the transducer with a deliberate degree of mismatch for the sake of widening the bandwidth.

Where the load is complex as in ultrasonic cleaning, a choice can be made between steel and dural for the front plate material. Some designs* make a special point of using a lighter metal as a front plate compared with the rear plate in order to maintain a wide operating bandwidth. This is a technique that has been used extensively on underwater projects for a long period of time. Insofar as a wide bandwidth can be achieved for ultrasonic cleaners by this means, very similar results can also be obtained by using dural both as a front and back plate.

3. The bias bolt.

The bolt through the assembly should be of high tensile steel and it is important that the diameters recommended are used. Where the bolt runs through the PZT ring a nylon or polythene sleeve should be used for insulating against high voltage breakdown.

* British Patent No. 868,784

bolt head is recessed into the front plate so that the front face can be bonded on to another structure if necessary.

The transducer is shown with two PZT rings connected in parallel electrically. This conveniently puts the two outside plates at the same potential. However, the transducer will operate just as satisfactorily if only one ring is used, providing some means is found for insulating the back plate from the front. It may be possible for instance to place insulating washers under the head of the bolt.

The use of epoxy resin is indicated on the drawing and it is worth noting that the finished transducer will have an upper temperature limit set by the resin rather than the PZT. Although transducers can be made without resin between the crystal and metal masses it is considered advisable to use resin as an acoustic couplant. The need for it as an internal adhesive is obviously reduced when a bias bolt is used.

The problem of securing adequate and consistent electrical connection to the outside PZT electrodes can be overcome by using a wire gauze between the PZT and metal plate. In construction the resin is allowed to flow freely over the gauze, care being taken to see that no air pockets are trapped in the mesh. Experiments have shown that a phosphor bronze or monel metal type is best with overall thickness about 0.003" and of 48 S.W.G. wire 250 mesh. The chief advantage of the wire gauze is to ensure absolute uniformity of the bond during assembly and to provide even distribution of the electrical connection.

DESIGN OF SANDWICH TRANSDUCERS

PZT4 Rings (two rings per transducer)	$1\frac{1}{2}$" O.D. x $\frac{1}{2}$" I.D. x $\frac{1}{4}$" thick	2" O.D. x $\frac{3}{4}$" I.D. x $\frac{1}{4}$" thick	$1\frac{1}{2}$" O.D. x $\frac{1}{2}$" I.D. x $\frac{1}{4}$" thick
Thickness of aluminium (or dural) - "A"	4.1 cm	4.1 cm	2.2 cm
Thickness of steel - "B"	2.5 cm	2.5 cm	1.25 cm
Diameter of plates - "C"	$1\frac{1}{2}$"	2"	$1\frac{1}{2}$"
Bolt size (high tensile)	$\frac{1}{4}$" dia.	5/16th" dia.	$\frac{1}{4}$" dia.
Applied torque lb.ins (bolt to run full length of steel, about $\frac{1}{2}$ length of Al.)	144	276	144
Induced load, psi	3,000	5,000	3,000
F_R Kc/s (may drop few % on attaching to water-filled tank)	25	25	About 43
δF Kc/s	2.0 - 2.5	2.0 - 2.5	About 5 - 7
Z_R (Ω)) depends on tank, i.e. thickness of steel plate on bottom, and also transducer spacing.	500 - 2,000	300 - 1,200	500 - 2,000
$Q_{mechanical}$)	12 - 3	12 - 3	12 - 3
Safe power, watts (continuous)	25 - 50	40 - 80	25 - 50

NOTE :- Cross-sectional area of ceramic assumed about same as steel and aluminium. δF higher if metal plates slightly larger diam. than ceramic - this tends to reduce F_R.

29th September 1965.