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Sandwich Transducers for Moderate Beamwidths

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1.0 Design requirements

For the lower frequencies, particularly below 20 KHz, occasionally up to 100 KHz, the sandwich transducer is a well-established design, most frequently of circular section in the form of a tapered head section, a stack of piezo-electric ceramic rings with an outside diameter around a half or a third of that of the head, and a heavy tail mass, the whole held together by epoxy resin bonds and a central pre-stressing bolt; the proportions of the parts can be easily varied, giving the designer a wide choice of parameters, in particular a lower Q being obtained by making the stack of smaller diameter than the radiating face. The major limitation to this technique is that the face has an optimum diameter of about 0.6 to 0.8 wavelengths (in water); with a smaller diameter more units are needed to cover a given area, and with a larger size a head driven over only the central part does not act as a rigid piston, so that the radiation load is lower than expected and the beamwidth wider. For the high frequency range, particularly above 200 KHz, single pieces of ceramic are used, although with some limitations on the maximum size. However the designer has to accept what the ceramic manufacturer can provide, and the bandwidth and electromechanical coupling can be varied in only a very restricted way by choice of piezoelectric material, but there is little restriction on the shape and size. For the intermediate range, around 100 to 200 KHz, the type of transducer most convenient to make is the sandwich element of constant cross-section. In this range, the thickness of a single piece of ceramic resonating in the "thickness" mode may be too thick for poling, and the small size of a tapered sandwich leads to difficulties in manufacture and additional uncertainties due to the finite thickness of the epoxy bonds. Furthermore, unless an array has to be subdivided into a number of small elements, e.g. for scanning or multiple beam forming, it is obviously uneconomic to use several transducers where a single one will do the job. When the radiating faces of these straight sandwiches are many wavelengths across, maybe ten or more, so that edge effects may be neglected, the design can be done by using "bulk" velocities and impedances, in exactly the same way that the "bar" parameters are used in the design of tapered sandwiches, although without the advantages of variable area. But for face sizes between the two extremes, mainly one to five wavelengths across in water, for both straight sandwiches and single ceramic plates the longitudinal or thickness resonances are not uniquely defined, and edge effects are of considerable importance; within the bulk of the materials infinitesimal elements are neither laterally free, as in narrow bars, nor laterally blocked as in infinite plates, and the effects of resonances which are functions of the cross-dimensions must be considered.

2.0 Piezo-electric plates and discs

The resonances of ceramic plates can be calculated, albeit with some difficulty, and the results for PZT-4 squares of varying thicknesses (from cubes to thin plates) and $BaTiO_3$ discs are given in ref. 1, but without any direct indication as to which of the resonances correspond to good radiating modes, and in general there are many resonances. The results of measurements on a few specimens are shown in fig.2, in which the Q due to loading by water is plotted against the face size in wavelengths, since this is the usual starting point for most designs. The 40 mm. $BaTiO_3$ disc was obtained as a 100 KHz element, with D/λ equal to $2\frac{3}{4}$, but at this frequency the Q is 60 (for the purposes of the present investigation a value of 30 is taken as the margin of acceptance, as this is the Q of a large PZT-4 plate); a much more useful result is obtained at 83 KHz, $D/\lambda = 2\frac{1}{4}$, Q = 36 (unfortunately neither the lowest resonance at 67 KHz nor that at 131 KHz were measured). The 32 mm. PZT-4 disc gives quite good Q's for all its lowest four resonances, the best being $28\frac{1}{2}$ for D/λ equal to 3.1. The 25mm. square PZT-4 plate was obtained as a 250 KHz element ($D/\lambda = 4.2$); [redacted] the Q at this resonance is rather high at 59, but the next two lower ones are much better, with Q's of 30 and 33. The lowest two resonances, not shown on the graph, have either a high Q or a low coupling coefficient, and this is probably due to this crystal being relatively thinner than the other two tested. It should be noted that the Q's given are due solely to loading by the water, any damping due to the simple mounting (foam rubber glued round to keep the water out) or to losses in the ceramic having been allowed for. A high loading Q indicates that there are significant amplitudes of vibration elsewhere than on the radiating face (and by symmetry on the back side), or, in an alternative expression, energy storage in modes of vibration which are only weakly coupled to the load. Thus any absorbing structures, such as part of the mounting, attached to the sides of the element can make the Q appear low, but giving a poor radiating efficiency. This may be acceptable in some applications, but it may be accompanied by unfavourable phase and amplitude distributions over the radiating face.

3.0 Sandwich Transducers

3.1 Description of the unit tested

A series of measurements have been carried out on a 25mm. square stack consisting of a 2mm. thick plate of PZT-4 bonded between equal lengths of aluminium alloy. A square section was chosen in preference to a circular one, because of the greater ease with which it could be ground to a uniform section after bonding and for ease of clamping while the head and tail are machined to length. At the start the total length was about twice the width.

3.2 Frequency spectrum of resonances

This is shown in fig.1. The axes are D/λ, the face width in wavelengths in water, and D/T, the width divided by the total length. The lowest resonant frequency for a thin bar is determined by the "bar" velocity, and this mode would appear on the graph as a straight line through the origin with a slope given by : bar velocity = velocity in water x $2(D/\lambda)/(D/T)$. The results for D/T up to 0.7 thus give the velocity in aluminium as 4.9 Km/sec, the ceramic with different velocity and impedance having probably little effect. Also shown is the line for infinite plates in the thickness mode, with an estimated velocity for aluminium of 6.6 Km/sec. For thinner shapes the frequency of this lowest mode varies less rapidly with T, being therefore controlled more by the width, and ultimately it must tend towards the lowest mode of the bare plate with D/λ equal to 1.16.

The next resonance shows initially no variation with thickness, and it is most probably a planar resonance of the ceramic with the faces blocked; with the faces free this mode has D/λ equal to 1.68. The third mode corresponds to the third harmonic of the principal length mode for a thin bar, but even at the thinnest shape tested the width in wavelengths in the metal is too great for the effective wave velocity to be that for a thin bar, and so the resonant frequency is not inversely proportional to length. As T is reduced, this mode splits into three, a phenomenon which theoretically cannot happen with homogeneous materials. The higher modes were not investigated in detail, because better results are obtained by using a mode more equivalent to a fundamental thickness mode, i.e. having D/T in the region of the line representing the bulk velocity.

3.3 Loaded bandwidths

The loaded measurements were done with the radiating face just dipping below the surface of the water, so that it was effectively unbaffled; the same results would not necessarily be obtained with the transducer mounted in a housing providing a baffle, but this is unlikely to affect the conclusions reached on the usefulness of the various modes. The unloaded Q's are generally in the range of 500 to 2000, the alloy having very low losses, and so efficiencies of over 95% have been obtained. The lowest mode is well behaved, with a minimum Q of 14 for D/λ about 0.85, rising to 27 at 1.5; however with the decreasing rate of change of frequency with T, not much change in D/λ is expected for this mode. The effective electromechanical coupling coefficient is high enough, increasing from 0.18 to 0.20 as the proportion of ceramic increases from 4% to 10% by volume. The second mode showed very little coupling to the water and detailed measurements have been omitted. The third mode started to show useful results only for $D/\lambda \geqq 2\frac{1}{2}$, and then for the two higher frequency resonances; at the time of writing the experimental work is still continuing, but the evidence so far is that resonances are probably useful if they lie somewhere near the frequencies predicted from the bar or bulk velocities. The main exception to this is in the region $1\frac{1}{2} \geqq D/\lambda \geqq 2\frac{1}{2}$, where the velocity is not clearly either "bar" or "bulk", and square transducers with aluminium alloy heads and tails cannot be made for this range, which gives beamwidths of 20° to 40°, a very convenient size for simple echo-sounders; there is a little evidence that this is true also for circular ones.

4.0 References

1. R. Holland, E. P. EerNisse, Design of Resonant Piezo-electric Devices, M. I. T. Press, 1969.

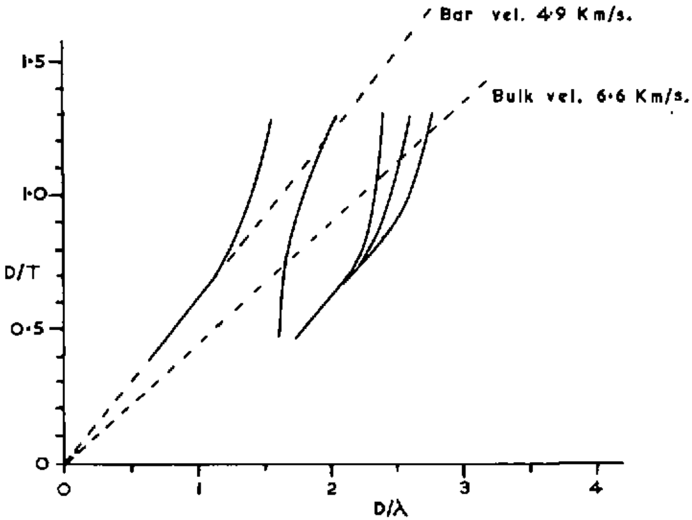

Fig.1 Frequency spectrum of sandwich element
Dural head and tail, D = 25 mm. square, 2mm. of PZT-4 at centre, total thickness T, wavelength in water λ.

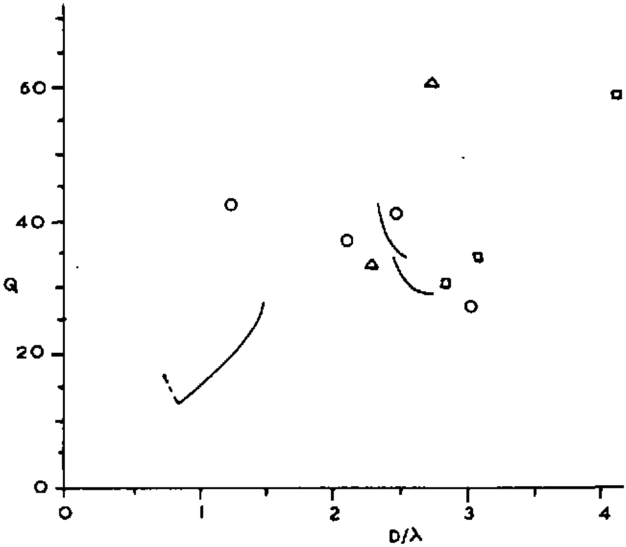

Fig.2 Bandwidth of sandwich element and ceramic plates
○ PZT-4 32 mm. dia. 12 mm. thick
□ " 25 mm. square 8 mm. "
△ $BaTiO_3$ 40 mm. dia. 27 mm. "
—— Sandwich element 25 mm. square