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A REVIEW OF PROBLEMS IN HIGH-FREQUENCY TRANSDUCERS

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1.0 Introduction

The types of transducer to be discussed are those in which the shape of the cross-section is constant in planes parallel to the radiating face through the thickness, the frequency being high and the size small so that the technique of changing the cross-section, which is so successful at low frequencies, cannot be used. Other methods have to be used to overcome this loss of freedom in the design. The general arrangement is indicated in fig.1, and the problem areas are identified there.

The face size may be any number of wavelengths in water, in contrast to the tapered low-frequency designs which are limited to a maximum of about two thirds of a wavelength, but there are some restrictions if maximum efficiency is to be obtained; this is discussed further in section 2. Backing and facing materials are required for mounting and protecting the elements; the desirable properties are discussed in section 3, and the acoustic properties of available materials are described by Pelmore(1). The most common high-frequency transducer element is a simple plate of piezoelectric ceramic, used near its resonant frequency in the thickness mode, but "sandwich" structures with passive materials on either side of the active ceramic have their advantages, which are discussed in section 4. Other problems which arise only in multi-element arrays are inter-element coupling and the selection of elements to make a well-matched set.

2.0 The size and shape of individual elements

The size of the radiating face is basically determined by the specification of the array for beamwidth and any subdivision for beam steering or amplitude tapering. The question then arises whether this size, which is most conveniently given in terms of the wavelength in water at the working frequency, is in fact suitable for efficient transmission or reception when the thickness is adjusted for resonance. The desired principal mode of vibration is in the thickness direction, i.e. normal to the radiating face; it is commonly assumed that this mode is pure for all the shapes likely to be used, i.e. that all the strains are in the thickness direction. This can occur ideally in an infinite plate only, but in practice of course the boundaries cannot be entirely neglected, and the resonant modes are in theory highly complex.

Methods of calculating resonant frequencies and effective electromechanical coupling coefficients have been developed by Holland and EerNisse[2], but unfortunately their work does not extend to considering whether the modes are likely to be efficient for acoustic radiation; this is an aspect which would make a worthwhile theoretical study. However in practice for transducers with faces several wavelengths across in both directions radiating into water the wanted thickness mode is usually dominant, unmistakeable and efficient. More difficult problems arise for the smaller sizes, in which the width and thickness may be of the same order of magnitude and the resonant frequency is controlled by the width as well as the thickness. Empirical results from work at Birmingham indicate that for narrow bars (small in one dimension) and for square plates, poor radiation occurs for sizes between $1\frac{1}{2}$ and 3 wavelengths in water, corresponding approximately to $\frac{1}{2}$ to 1 wavelength in the ceramic for bulk waves. It is probable that in this forbidden range the bulk of the stored energy is in alternating strains in the planes parallel to the radiating face rather than normal to it. There are probably also defects in the directional pattern; it is usually assumed that the normal surface velocity is uniform over the radiating face, but this is not necessarily true, particularly for sizes in the forbidden range. For smaller sizes, with wide beamwidths, the variations are not very important, and for larger sizes they are probably small except near the edges. This is another field where further investigations would be useful.

3.0 Backing and facing materials

3.1 General aspects

The primary functions are that the backing should support the elements accurately and isolate them from the rest of the housing, and that the facing should protect them from the water while being acoustically transparent; the acoustic properties may be chosen to emphasise particular aspects of the performance. The desirable properties are summarised in table 1. One common property is that both should be electrically insulating, so that the transducer is not short-circuited, and another that they should have low absorption of water, so that the transducer remains protected even after long periods of immersion at great depths. Water absorption in the backing material may not be so serious, as the design can be arranged so that the primary protection is by the facing material.

3.2 Backing materials

The two properties which are most desirable for many applications are high stiffness at zero frequency and a low acoustic impedance at the working frequency. Unfortunately these can be compatible generally only if the material has a very low density, much less than water; no such material exists with sufficient strength, and so there has to be a compromise. The high stiffness is required so that the elements are held securely in position even under considerable hydrostatic pressure (any movement affects the alignment in a multi-element array and may affect the watertight integrity depending on the design), and the low impedance so that the acoustic load on the rear of the transducer is minimised for maximum efficiency on transmission and minimum noise figure on reception. However there are often occasions when the additional loading is useful in broadening the bandwidth, which is generally much narrower than for typical low-frequency designs. Another desirable property is a high acoustic attenuation, so that a thin layer can be used without the reflected waves from the rear of the housing being at a high enough amplitude to cause variations in the effective load on the transducer; a thin layer is preferred both to reduce the overall size of the array and to reduce the deflection under pressure. Very useful data on attenuation and impedance are to be found in Pelmore's contribution[(1)].

3.3 Facing materials

The transducer needs to be protected from mechanical damage and chemical attack, and it is usually best to insulate it electrically from the water. There are broadly speaking two schemes for covering the elements. The older method is to select a material with an acoustic impedance very close to that of water and to use any convenient thickness for mechanical protection, the facing being acoustically indistinguishable from water. Traditionally castor oil within a rubber boot has been used, having the advantages of a closely matched impedance and chemical compatibility with the other materials; being a fluid, it is excellent for absorbing uneven shock loading.

The newer method is to use a material with an acoustic impedance between that of water and that of the ceramic. In one version it is exactly half a wavelength thick so that it does not affect the resonant frequency, loaded or unloaded, nor the load on the transducer at resonance, but it always narrows the bandwidth, since there is additional energy storage for the same radiation. In another version, it is made a quarter of a wavelength thick and so can act as an impedance transformer between the transducer and the water; one difficulty is that the resonant frequencies in air and water are quite different. This design is discussed in more detail in section 4. If a solid material, such as metal, is used for this kind of front plate, it can be extended beyond the limits of the active plate, perhaps with grooves to reduce the coupling, so that it can form the front cover of an air-filled housing, and there is then no need for a backing to support the elements. This scheme has the disadvantage of being critically dependent on the quality of the bonding, without any hydrostatic pressure providing some pre-stressing, but on the other hand the efficiency is maximised.

4.0 Composite assemblies

A simple lead zirconate-titanate plate, air-backed and radiating into water, has a rather narrow bandwidth, the Q being about 30, because the ceramic has a much higher acoustic impedance than water (about 23 times). In order to improve the bandwidth and the impulse response, composite assemblies may be used; these consist of a "sandwich" of active material between layers of passive material generally about a quarter of a wavelength thick or less. This type of transducer can be divided into two classes, as indicated in fig.2.

The first version is very similar to the low-frequency tapered-piston type, having three sections and resonant overall at the lowest longitudinal or thickness mode. However the design has usually to be done using the transmission line analysis, since the approximations used in the "lumped element" approach are not valid. The best design requires a low impedance material for the head section and a high impedance one for the tail, which can be omitted (i.e. made of piezoelectric material), and the proportion of active material may be quite low, e.g., as little as 10% by volume, while still giving a high enough effective coupling coefficient for the complete transducer. Ideally the head section should have a length approaching a quarter wave. This structure can be used with a supporting backing with a smaller loss of efficiency than with a simpler element. The disadvantages are that pre-stressing bolts cannot be used effectively in the way they can for low frequency elements, and the bonds are generally in planes of high alternating stress, so that the relatively high compliance of the bonding materials have to be taken into account in the design, also their losses may be significant.

The alternative approach is by coupling the basic half-wave active plate to the load and perhaps also to the backing through matching sections. The simplest design uses a quarter wave plate of a material with an intermediate impedance, and this has been investigated theoretically and practically by Kossoff[3]. The widest bandwidth is obtained by matching to the load and to the backing, but the impulse response was not improved quite to the extent expected from the bandwidth measured by the response to continuous signals over a range of frequencies. A more complicated approach is to divide the quarter wave section into a number of layers with impedances graded from the ceramic to the water; this gives a greater freedom in the design and considerable improvements in the impulse response have been obtained theoretically by Pace[4].

5.0 Inter-element coupling

This can give rise to two effects. Firstly the mechanical load on one element depeneds on the electrical drive to the other elements in a transmitting array; it is probably complex, and if the coupling is high, the real part can even be negative. Thus the electrical impedance may not be the expected "free" value. Secondly the directional pattern is distorted and can change in an irregular manner if the beam is steered by phase shifts in the electrical circuits. The coupling need only be considered in multi-element arrays in which the spacing of the elements, centre to centre, is less than a wavelength or so, and it can take place through several mechanisms. The unavoidable route is through the fluid medium in front of the array; this can be analysed theoretically[5], and it is generally negligible for spacings of more than half a wavelength. If there is a continuous solid layer in front of the separate elements, there can be coupling due to shear waves travelling in the plane of the array, and the same effect can happen in the backing. Another effect in the backing is transmission from one element to another via a reflection from the back of the housing, and this is another reason for having high attenuation there; this is likely to be a significant route for larger elements, and has not been considered seriously enough in the past. The final route for coupling is directly between the sides of the elements, and it is probably greatest for elements with shapes such that the frequency is determined to a significant degree by the width. This coupling can be minimised by having a highly complient material in the gap between elements; ideally it would be air, but there may be problems of resistance to hydrostatic pressure and accurate assembly of the array, and so a solid material will probably have to be used in most cases. The spacing is usually much too small for the attenuation in the spacer to be significant.

A practical problem is the relation between simple electrical measurements of the coupling and the real acoustic effects, such as the distortion of the directional pattern and the degradation of resolution. Some general theoretical analysis seems to suggest that the effective acoustic coupling is much higher than the electrical coupling, measured as a voltage ratio from one element to another. This is an area which would benefit from a closer analysis, so that more meaningful specifications can be written.

6.0 The selection of elements for multi-element arrays

It is highly desirable that all the elements in array should have identical resonant frequencies, conductances at resonance and effective coupling coefficients. For low-frequency arrays, the elements can be tested in the final mounting and then selected into matched sets, since the elements can be changed in position without difficulty. On the other hand, high-frequency arrays are made as complete units and it is much more difficult, if not impossible, to change the elements thereafter. Therefore it is necessary to select elements on the basis of measurements on the unloaded and unmounted units, and the question arises as to which are the most significant parameters out of free resonant frequency, coupling coefficient, capacitance (free or clamped), motional capacitance and inductance. For the larger plates, i.e. with face dimensions more than three wavelengths in water, the changes in mounting them should be due only to the increased radiation loading, but for small elements the loading is partly reactive and there is also the complex change in loading on the sides of the elements. In the finished array uniformity of frequency is probably the most important, since the bandwidth is usually small and errors in phase are more difficult to measure and correct than errors in amplitude. If there is an unavoidable spread in frequencies, it is preferable for the elements to be in order of frequency, so that there is an average phase taper across the array, causing an offset in the position of the main beam and minimising the distortion. But the problem is still how to predict the likely shifts in frequency between the unmounted state and the final assembly, and this is likely to be greatest for elements with nearly equal width and thickness.

7.0 References

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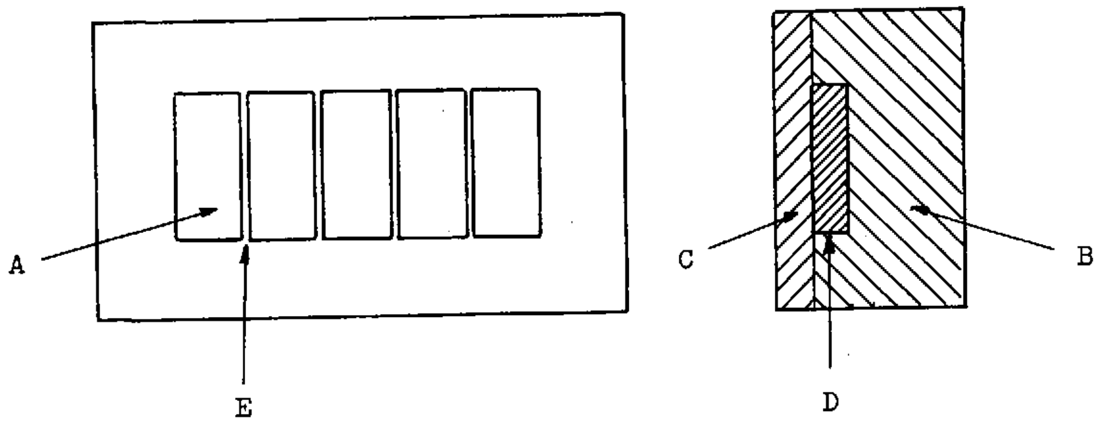
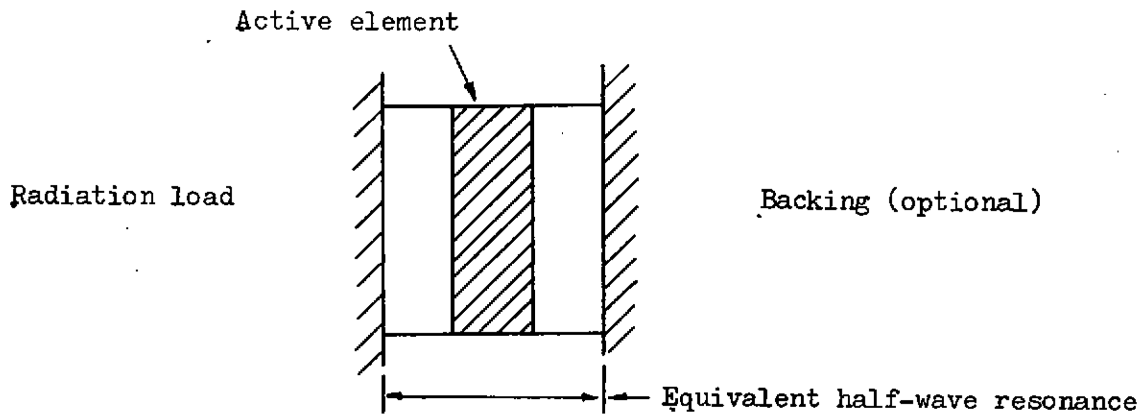
Facing Materials	Backing Materials
Low attenuation	High attenuation
Matched to load, or intermediate impedance	Low impedance
Resistant to mechanical damage	Stiff to hydrostatic pressure
Electrically insulating	Electrically insulating
Low water absorption	Low water absorption

Table 1 Desirable properties for materials used in mounting transducer elements.

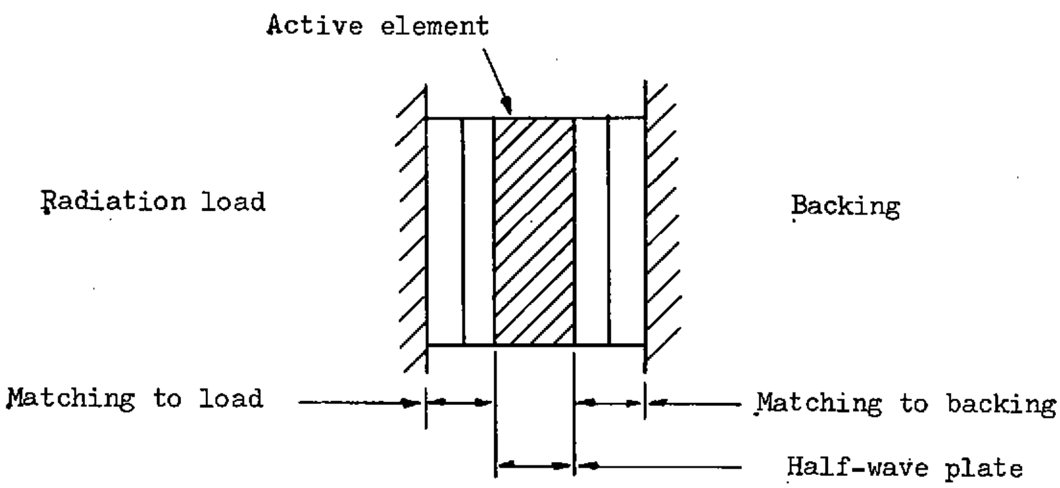


A Size and shape of elements
B Backing materials
C Facing materials
D Composite assemblies
E Inter-element coupling
F Selection of elements

Fig.1 General arrangement and problem areas.



(a) Three-section sandwich structure



(b) Simple plate with matching sections

Fig.2 Composite structures