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PROCEEDINGS OF THE
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TRANSDUCER WORKSHOP

HELD IN THE DEPARTMENT OF
ELECTRONIC AND ELECTRICAL ENGINEERING,
UNIVERSITY OF BIRMINGHAM

15th DECEMBER 1976

TRANSDUCER WORKSHOP

This was the second specialist meeting of the Underwater Acoustics Group (UAG) of the Institute of Acoustics. It was a one-day meeting held in the Department of Electronic and Electrical Engineering, University of Birmingham and attended by 61 people.

The main object of the meeting was to highlight problems encountered in the design and production of transducers used in underwater acoustics by bringing together designers and users. The contributions were mainly in the form of case histories in which specific designs were described. It was hoped by this method to generate useful discussions. However, in the event because of the full programme and other associated problems the discussions were felt to be insufficient to justify including them in this publication.

The Committee of the UAG wish to record their appreciation for the support and facilities made available by Professor H.A.Prime, Head of Department.

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LOW FREQUENCY TRANSDUCERS

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Introduction

Any sonar system, or any sonar experiment, needs a transducer as the link between the electrical components and the acoustic path in the water. Transducers thus form an essential component of such systems, and this paper reviews the main features and problems associated with the generation or reception of underwater sound within the frequency range of 1 to 100 kHz. It is important to remember that a transducer is a part of a system, and its interaction with the other components must be taken into account during its design. The acoustic requirement often needs an array of transducers, and here again the element design must be based on the characteristics needed of the array. Thus, the basic features of a transducer depend on its interaction with the other components of the system (largely electrical) and with other transducers in an array (largely acoustic). The realisation of the design is primarily an exercise in mechanical engineering.

This paper will concentrate on the electrical interaction with the system, and on the mechanical aspects. The influence of the array characteristics, although important, will be mentioned only briefly.

The wide dynamic range of commonly used transducers is worth noting. Output power densities of at least 1 watt/cm^2 are quite common for transmitting transducers, and these same elements may be used also for receiving background noise which is less than 10^{-12} watt/cm^2. The materials are such that the transducers are very nearly linear over this wide range, and it is therefore common for transducers to be used for both transmission and reception. Figure 1 shows typical amplitudes of vibration in a plane wave in water; the very small amplitudes involved suggest that the driving mechanism in an underwater transducer should have a high stiffness (compared for example to the flexible drive of a loudspeaker for use in air), and such is indeed the case.

The commonest active materials for underwater transducers are the electrostrictive ceramics, Barium Titanate and Lead Zirconate Titanate (LZT). After poling by application of a high DC electric field, these materials behave like the true piezoelectric crystals such as quartz or ammonium dihydrogen phosphate (ADP), which now have only limited use. The most useful parameter describing the piezoelectric activity of the material is its coupling coefficient (denoted by "k" with a subscript indicating the mode of vibration). The factor k^2 has great significance in analysing the behaviour of a transducer. In physical terms it represents the ratio of the stored mechanical energy to the total stored (mechanical plus electrical) energy when an electrical field is applied; in practical terms k^2 determines the bandwidth over which efficient conversion of electrical to acoustic energy is possible. The other major parameter of the material is its dielectric constant (E), which largely determines the transducer impedance. Values of these parameters are given in many references (eg Ref 1). For a high power transmitting transducer, high values of both E and k^2 are wanted (together with a low dielectric loss factor). For a receiver, lower values of E may be acceptable for some applications, and also higher dielectric loss factors, thus permitting a wider range of materials.

Hydrophones

The main requirements to be specified for a receiving hydrophone are its bandwidth limits and its beam pattern. The implications of the beam pattern requirement are usually easy to determine from standard texts (eg Ref 2). The beamwidth (θ) (to the −3 dB points) in a plane parallel to one edge of a rectangular plane piston transducer is given by

$$\theta \approx 50^\circ \lambda/L$$

where L is the length of the piston, and λ is the wavelength of sound in water. For beamwidths narrower than 50°, transducer dimensions greater than λ are needed. Since the speed of sound in most transducer materials is 2-3 times that in water, this implies that transducer dimensions approach or exceed $\lambda/2$ for the material itself. Such dimensions incur the risk of unwanted resonances within the transducer, and it is therefore generally safer to avoid potential problems by dividing the radiating surface into an array of transducer elements, even though the assembly may be more complex. If electrical beamsteering is required, division of the array into elements separated by $\lambda/2$ (for water) is usually appropriate, and this should avoid most of the dangers of unwanted resonances within the elements themselves.

For many applications, hydrophones are required which are omni-directional in one plane or more. In principle this is easy to achieve, either by using receivers which are small fractions of the wavelength of sound in water, or by using elements of suitable symmetry (eg cylinders or spheres). However, great care is needed to avoid problems arising from unwanted resonances and directivity associated with the mounting arrangements.

In some cases, directional response is required from a hydrophone which is restricted to a size which is only a fraction of a wavelength. This may be achieved (for example) by connecting two pressure sensors in anti-phase to form a dipole. Combined with an omni-directional sensor, this may be used to generate a cardioid (or more generally a limacon) directional pattern, with a single major lobe. The price to be paid for this directivity is a loss of sensitivity and a greater dependence on tolerances, but with care satisfactory cardioid patterns and signal/noise can be achieved down to element spacings of about 0.025λ. Such a combination may be regarded as one simple form of superdirectivity, and more complex combinations may of course be postulated.

Hydrophones are frequently required to have a sensitivity which is essentially independent of frequency over a wide operating band. This is usually achieved by placing the basic resonance frequency of the hydrophone well above the maximum operating frequency. Piezo-ceramic hydrophones have a flat frequency response below resonance, provided other mounting resonances do not obtrude. The low frequency limit is then generally determined by the input impedance of the receiving amplifier combined with the hydrophone capacitance. If a low cut-off frequency is wanted, and to avoid signal/noise problems, it is desirable to make the hydrophone resonance not too far above the top of the working band, thus maximising the volume of the active material. Another source of unwanted noise, as well as of mechanical resonances, is the coupling of the hydrophone element to its mounting. If the mounting is subject to vibrational excitation, this may be transferred mechanically to the element, which often has an acceleration sensitivity. This problem may be tackled either by devising better isolation of the element from its mounting, or by using balanced ("acceleration-cancelling") elements which have a lower sensitivity to acceleration. For example, a piston hydrophone may be constructed as two symmetrical halves about a central mounting plate, the two halves giving outputs which reinforce for applied pressure fields but oppose each other for axial vibration of the mounting. It is important to remember that this cancellation is not perfect, and that mounting resonances should still be avoided. For more details of these factors, see Ref 3.

In most applications in sea water, hydrophone sensitivity is not in itself a problem, since it is usually fairly easy to obtain sufficient sensitivity to overcome electronic noise unless very wide bands are required. Reliable low-noise pre-amplifiers are reasonably easy to obtain and use if signals need to be transmitted along long cable lengths. If only narrow band operation is needed, however, hydrophone elements may be used near their resonance frequency, thus giving enhanced sensitivity which may sometimes be of advantage, although the increased dependence on tolerances should be remembered.

<u>Projectors</u>

The basic acoustic features to be specified for a transmitting transducer are:-

a. resonance frequency and operating bandwidth.

b. power output.

c. directional characteristics.

Various other factors such as weight, compatibility with other materials, and overall efficiency are usually also specified. Directional characteristics influence the design generally as already discussed for hydrophone arrays.

The transducer is just one part, though an essential one, of the system for converting electrical to acoustic energy. It is usual to require that this conversion should be carried out with an efficiency greater than some specified value, and this implies both that the conversion efficiency of the transducer itself is high enough, and also that energy is driven into the transducer with a high enough efficiency. This usually means that the transducer should be used within a band around its mechanical resonance frequency. For low frequency piezo-ceramic transducers, electrical/acoustic efficiencies at resonance in excess of 70% are quite practical, and it is worth remembering that the efficiency may remain reasonably high for quite large frequency deviations from resonance (eg See Fig 2). This is useful when excess power is available from the amplifier.

However, in more demanding applications when amplifier power is limited, good efficiency of power transfer into the load is necessary, and consideration of the matching of the transducer and driving amplifier is then important.

Equivalent circuits

Analysis of the electrical matching is carried out by means of the electrical equivalent circuit of the transducer. This is the circuit which exhibits a variation of impedance (at least over a frequency range near resonance) similar to that of the transducer. For piezoceramic transducers the simple circuit shown in Fig 3 is generally applicable. In this circuit, C_1, L_1, R_1 represent the mechanical resonance, and C_2 the dielectric (clamped) capacitance of the ceramic, with R_2 representing the dielectric loss of the ceramic. Fig 3 also indicates the relationships between these circuit components and the basic transducer parameters:-

w_s = $2\pi f_s$ where f_s = mechanical resonance frequency.

Q_m = mechanical Q-factor.

k = coupling coefficient of transducer.

C_{LF} = capacitance at low frequency (well below f_s).

$\tan\delta$ = dielectric loss factor of transducer.

The load presented to the amplifier at the resonance frequency of the transducer may be made resistive by tuning out the capacitance C_2 by means of a parallel tuning inductor L_2, and the system then resembles a half-section band-pass filter (Fig 4). Analysis of such a circuit by standard filter relationships gives expressions for the variation of the transducer input admittance and power transfer. For reasonable limits of transducer load presented to the amplifier (eg 2:1 variation in magnitude of the admittance, and a minimum load factor of 0.8), the maximum bandwidth is achieved when $Q_m k^1 \approx 1.2$, where $(k^1)^2 = k^2/(1 - k^2)$. The fractional bandwidth is then approximately equal to k^1, and the source impedance (Rs) for optimum power transfer over the pass band should be related to the load by $R_s \approx (1.2)^2 R_1$.

This is one example of the use of the equivalent circuit for analysing behaviour of the transducer as part of the system. More complex circuits for further widening of the operating bandwidth may be derived from relationships for higher order filters (Ref 4). The equivalent circuit may also be made slightly more complex (as in Fig 5) to show the distinction between the acoustic radiation load ($R_a + jX_a$) and the internal loss resistance (R_i). Values of these components may be derived from measurements in air and water, and permit calculation of the transducer efficiency. More complex equivalent circuits may be derived, and are useful for some particular studies, but for many purposes a circuit as shown in Fig 5 is sufficient, and is essential in understanding the transducer behaviour.

The equivalent circuit is also useful in understanding the behaviour of hydrophones, the effect of pressure being represented in this case by a voltage source in the motional arm. Examples of the predicted behaviour, applied to the design of wide band hydrophones, are given in Ref 5.

Transducer Constructions

Consideration of the array acoustic requirement, and the matching to the electrical system, determines the characteristics required of the transducer elements themselves. Realisation of these characteristics makes use of a variety of types of transducer constructions, one review of which is given in Ref 6. When an electric field is applied to a piezoelectric material, mechanical strain is produced, but expansion along one axis is usually accompanied by contractions along the other axes in such a way that only small volume changes result. The basic feature of most designs is therefore to make best use of the strain along one axis whilst preventing radiation from the other axes, usually by ensuring that these axes are acoustically mismatched by driving into a very low impedance.

Amongst the most commonly used transducer designs for operation between 1 and 100 kHz are:-

a. Arrays of loaded ceramic blocks in oil.

The blocks are loaded with metal end-pieces to reduce the frequency, and non-intercellular rubber is usually used to prevent radiation from the back and sides. This construction is most suitable for frequencies near 100 kHz. It is simple in design, but needs care in assembly and oil-filling.

b. Piston-type transducers

This is probably the most commonly used type for transducers in the 3 - 60 kHz range. The ceramic stack has a radiating piston at one end, and a mass at the other end which may be another radiating piston or (more commonly) an inertial counter-mass in air. The radiating piston is mounted in an air-filled housing so that the rear of the piston, and the ceramic and countermass are all in air. The element may be balanced (ie counter-mass approximately equal to piston mass), or unbalanced (counter-mass several times the piston mass). The balanced construction is easy to mount by means of a plate or diaphragm at its mid-point, and then has some decoupling (and acceleration-cancelling as a hydrophone) from its case. The effective vibrating mass is approximately twice the piston mass, and values of Q_m of 5 to 20 in water are typical.

In order to reduce the value of Q_m, to achieve maximum bandwidth, an unbalanced design may be used. If the ratio of radiating mass (M_r) to counter-mass is m, the effective vibrating mass is given by $M_r(1+m)$. Use of lightweight aluminium or titanium pistons and counter-mass/piston mass ratios of 5 to 10 make values of Q_m down to about 3 possible. These values make it practical to match the effective coupling coefficient of a barium titanate transducer (usually in the range 0.20 to 0.30), and thus obtain a fractional bandwidth up to 0.3. For a lead zirconate titanate transducer, an effective coupling coefficient up to 0.5 could be realised, but there is considerable difficulty in reducing the Q_m value to match this, and a fractional bandwidth up to about 0.4 is more likely, particularly at low frequencies. For the higher frequencies it is more difficult to achieve these low Q_m values.

Unbalanced elements are commonly mounted to the case through a spring of some type, in order to provide some decoupling. Analysis of the mass and spring system is straightforward, at least at low frequencies where the lumped mass and spring approximation may be assumed, and also provided the springs behave linearly. For low frequency transducers, a centre bolt through the ceramic is common, to provide a static compression to the element and thus prevent the joints in the stack ever being subject to a tensile force. For resonance-frequencies above 20 - 30 kHz it becomes more difficult to find room for such a centre bolt, but its use is still desirable.

These piston transducers have a wide range of designs and applications. Designs can be analysed mechanically to a fair degree of approximation, particularly for the lower frequencies, and can be related also to their equivalent circuits. The main problems arise in ensuring watertightness, good joints in the stack, and satisfactory tolerances.

c. Magnetostrictive transducers

Magnetostrictive transducers using nickel or permendur have been used, mainly in the 20 - 60 kHz range, but have been largely superseded by the piezoelectric ceramic designs. Stacks of laminations are cemented together, and radiate from one end, radiation from other surfaces being reduced by means of cellular rubber. For some applications scroll-wound rings have been used, usually with cellular rubber on the unwanted surfaces, but useful efficiency can sometimes be obtained with free-flooding rings without any pressure-release rubber. Magneto-strictive transducers have the apparent advantage of robustness, but in practice some care in protecting the windings is needed. Efficiency and bandwidth are generally lower than for piezo-ceramic transducers, but for some applications their simplicity and low cost make them attractive, particularly where scroll-wound rings are suitable.

d. Free-flooding rings

The use of magneto-strictive rings without cellular rubber has already been mentioned, and similar designs are possible also for ceramic cylinders (Ref 7). These are particularly useful as deep sound sources which are omni-directional in one plane (usually the horizontal plane), and arrays of cylinders on a common axis may be used to give directivity in the other planes and to improve the efficiency. Resonance frequencies are determined primarily by the size of cylinder. For cylinders made as a single piece, ceramic manufacturing problems would generally limit frequencies to lie above about 6 kHz. Lower resonance frequencies are possible by assembling the ring from many pieces (like barrel staves), with the attendant assembly problems and higher cost.

e. Bender transducers

None of the designs mentioned above is very well suited to operate at frequencies below about 5 kHz. In order to generate high power at these frequencies, excursions of the piston face become relatively large (Fig 1), and a more compliant driving system becomes necessary.

This leads to the design of piezo-ceramic transducers in which the ceramic is used in bending instead of in a compressional mode. This more compliant structure makes it much easier to achieve low resonance frequencies from a small size element. A variety of designs exists, generally having a ceramic disc cemented either to another ceramic disc driven in opposition, or to an inactive metal disc (Ref 8). Although the resonance frequency can be made low for a small transducer, the radiation resistance is also quite low, and this is a disadvantage if broad-band operation is wanted. Also, because it is difficult to pre-stress the ceramic reliably, power output and operating depths are somewhat limited. These designs do however constitute the main approach to transducers resonant in the 1 - 5 kHz range, particularly for moderate output powers or as resonant hydrophones.

Problems

What are the problems in the design and use of transducers within this frequency range? In general, it appears that design of suitable elements for most applications is possible, and no major breakthrough appears to be needed. The areas where difficulties do arise appear to be in the engineering realisation of basic designs and in their integration with other parts of the system. Although basic design principles are reasonably well established, insufficient attention seems to be paid to deriving reliable design relationship in detail, so that transducers could be designed as a scientific or engineering discipline rather than as the "black art" which is too commonly the impression. Largely as a result of this, development times for reliable transducers are longer than they would be if a secure base of knowledge existed. On the other hand, a greater knowledge and appreciation of transducer potentialities and problems by the user should lead to more realistic demands and specifications.

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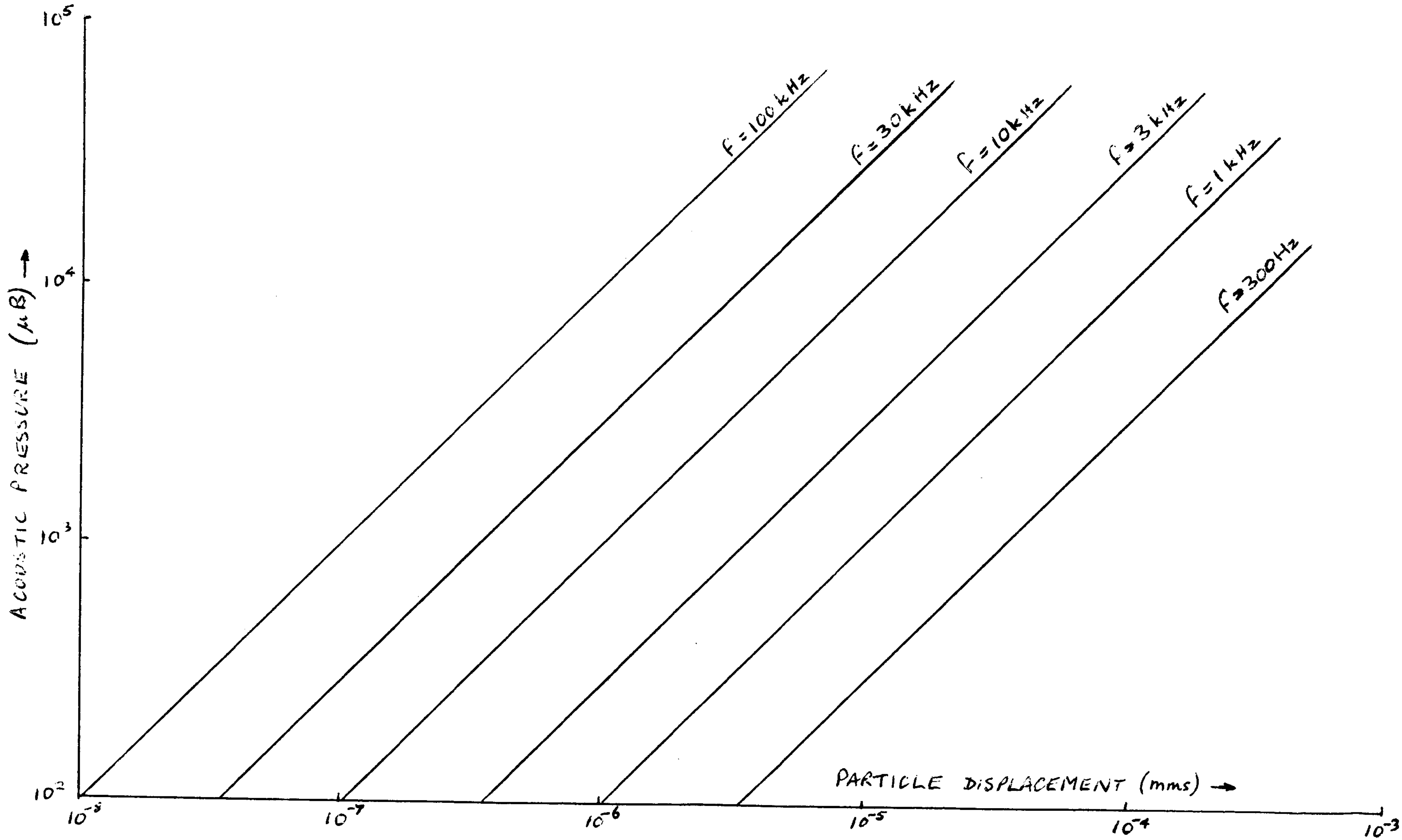
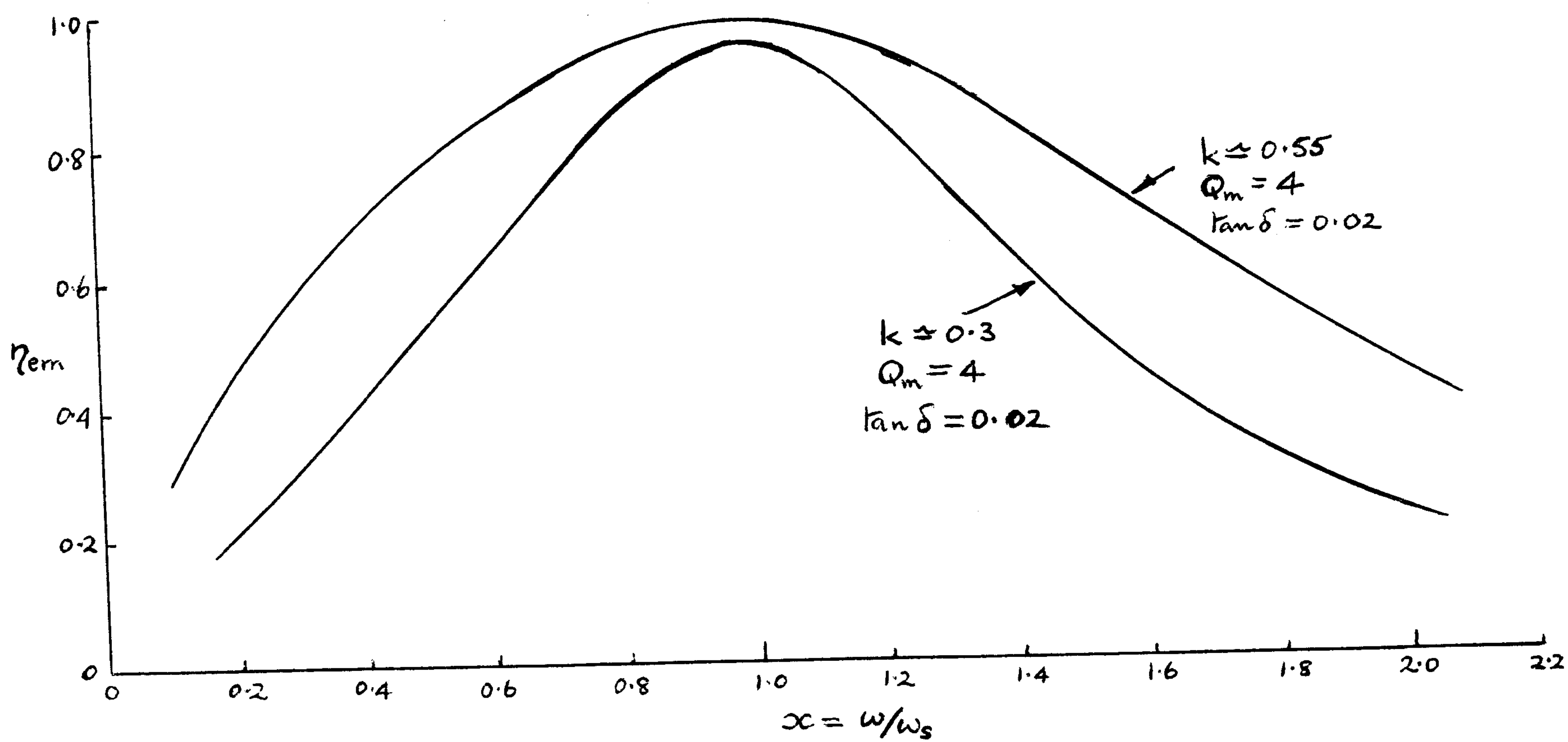


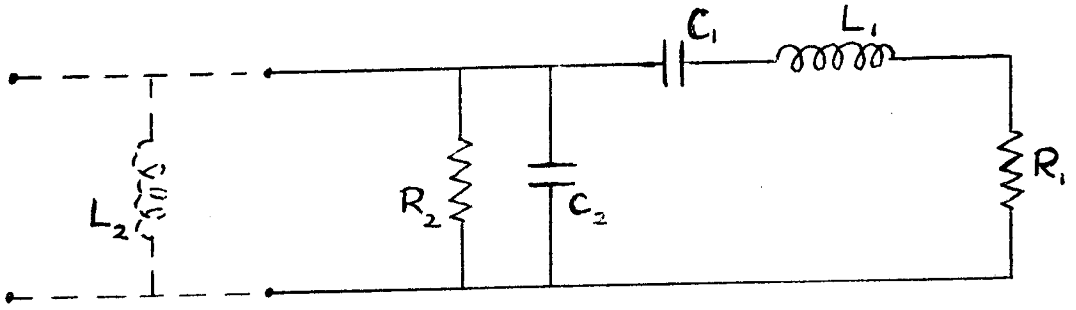
RELATION BETWEEN PARTICLE DISPLACEMENT AND PRESSURE FOR PLANE SOUND WAVE IN WATER.

FIGURE 1



VARIATION OF EFFICIENCY η_{em} WITH FREQUENCY

FIGURE 2.



$$w_s = 2\pi f_s = \sqrt{\frac{1}{L_1 C_1}}$$

$$Q_m = \frac{w_s L_1}{R_1} = \frac{1}{w_s C_1 R_1}$$

$$k^2 = \frac{C_1}{C_1 + C_2}$$

$$C_{LF} = C_1 + C_2$$

$$\tan \delta = \frac{1}{w\ C_2\ R_2}$$

(Parameters)

$$C_1 = k^2 C_{LF}$$

$$L_1 = \frac{1}{w_s^2 C_1}$$

$$R_1 = \frac{1}{w_s C_1 Q_m} = \frac{1}{w_s k^2 C_{LF} Q_m}$$

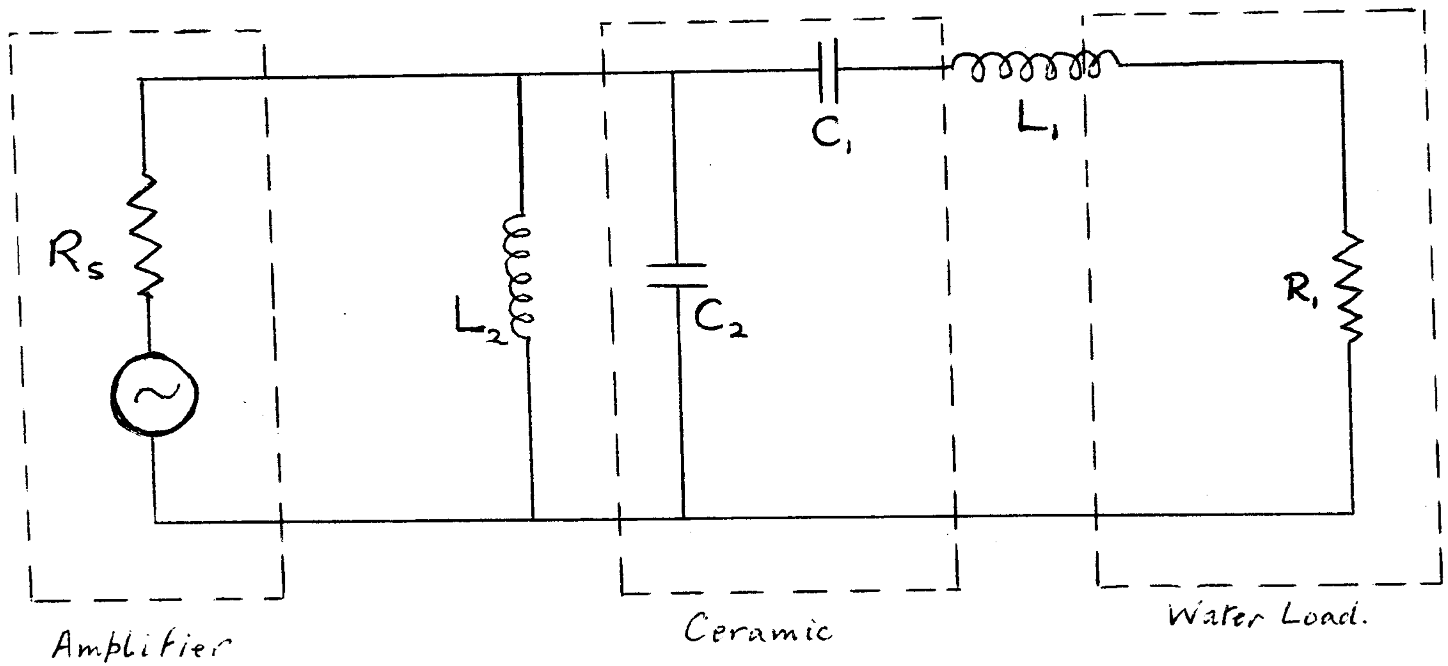
$$C_2 = (1 - k^2)\ C_{LF}$$

$$R_2 = \frac{1}{w\ C_2\ \tan\delta}$$

(Components)

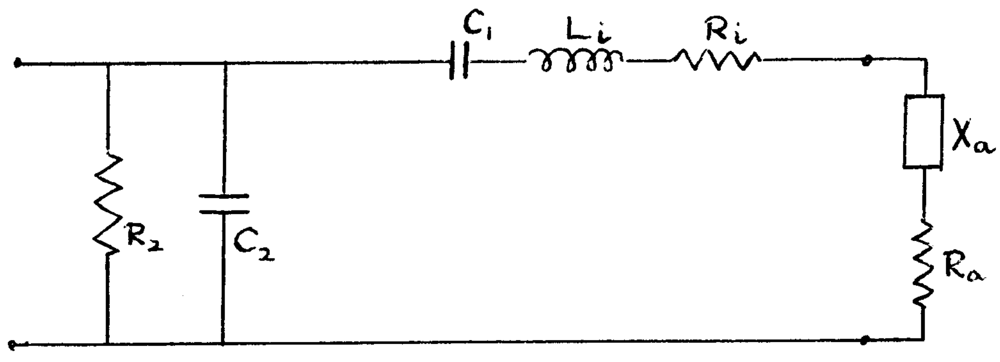
TRANSDUCER EQUIVALENT CIRCUIT

FIGURE 3



TRANSDUCER AS HALF-SECTION BAND-PASS FILTER.

FIGURE 4.



EQUIVALENT CIRCUIT SHOWING INTERNAL LOSS (R_i) AND RADIATION LOAD ($R_a + jX_a$)

Mechanical - Acoustic Efficiency $\eta_{ma} = \frac{R_a}{R_m}$

Electrical - Mechanical Efficiency $\eta_{em} = \frac{R_2}{R_2 + R_m}$

Electrical - Acoustic Efficiency $\eta_{ea} = \frac{R_a}{R_m}\left(\frac{R_2}{R_2 + R_m}\right)$

where $R_m = R_a + R_i$

FIGURE 5