BRITISH ACOUSTICAL SOCIETY

Electro-acoustic Transducers in Air and Water

23rd. January 1970

70/03

A Review of Underwater Acoustic Transducers

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1.0 Introduction

In this context a transducer is a device for converting one form of energy into a propagating acoustic field or vice versa, the energy being stored in electrical, chemical or mechanical forms. Transducers for transmitting applications are often referred to as projectors, and those for receiving acoustic waves as hydrophones, but the most frequently used types are equally suitable as either, and these are all electrical. The mechanical and chemical types are used as powerful sources, examples being explosives and hydraulic devices, but these are usually controlled electrically. The electrical types depend on the interaction of either charges with an electric field or poles with a magnetic field, the connections to the external electrical circuits being through conducting surfaces and coils respectively.

2.0 Electric field systems

2.1 General description

Three types have some practical applications, dielectric, piezoelectric and electrostrictive. The dielectric mechanism, as exemplified by the capacitor microphone for use in air, uses the interaction of two sets of charges; presumably because it offers no advantages over the other types in regard to sensitivity and robustness, it has hardly ever been used underwater, although this is possible with a solid dielectric. The piezoelectric effect, depending on the distortion of an unsymmetrical crystal lattice in an electric field, is frequently used, examples of crystals with useful properties being quartz, Rochelle salt and ammonium dihydrogen phosphate (ADP). These have to a large extent been superseded by materials depending on the electrostrictive effect, the mechanism of which is domain alignment in an electric field; the two important materials are barium titanate and lead zirconate. The distortion is proportional to the square of the field intensity, and so for linear operation a polarising field must be incorporated. Since the unpoled material is isotropic, poling can be in any direction, so that curved transducers can be made, and this is impossible with piezoelectric materials, in which the directions of interactions are in planes determined by the structure of the crystals. The electrostrictive materials are bonded with suitable additives for improving their characteristics and fired like ceramics (they are commonly referred to as such), and they generally have higher coupling between their electrical and mechanical properties than the natural crystals, but generally no distinction is made between the two types in their applications.

2.2 Non-resonant applications

The desirable property here for a hydrophone is a constant sensitivity (the ratio of output voltage to free-field acoustic pressure) over a wide range of frequency, the upper limit being set by the lowest frequency of mechanical resonance of the transducer and the lower limit ultimately by the leakage resistance of the material. By reciprocity, such a transducer can function as a broad-band projector if it is driven by a constant-current source, but this is not commonly done except in calibration procedures. For most materials a solid rectangular block with electrodes on a pair of opposing faces and all faces exposed to the pressure has a very low sensitivity, because the piezoelectric effects in the three orthogonal directions very nearly cancel out, but lithium sulphate is an exception in having a high hydrostatic sensitivity. Therefore more complicated designs are required, and hollow spheres and tubes with electrodes on the curved surfaces are frequently used. Spheres have the advantage of needing virtually no mounting; they can be suspended on their leads in oil in a plastic tube or a rubber bag, or moulded in rubber. Tubes need end caps to shield the inside from the signal pressures, and so are best moulded in rubber or plastic. Spheres are relatively insensitive in giving outputs due to acceleration in any direction, but tubes are available in a wider range of sizes. Another possible arrangement is with one or two discs forming part of a pill-box shaped housing, but this has the disadvantage that the ceramic is in tension due to the hydrostatic pressure, whereas in tubes and spheres it is always in compression.

2.3 Resonant applications

The simplest resonant transducer is a plate driven electrically in the same direction as the poling, or an X-cut quartz crystal, with the thickness corresponding to half a wavelength, and this is the lowest frequency of resonance in the "free-free" mode. Generally it is not possible to use the "free-blocked" or quarter-wave mode, because it is not possible to have a backing material with an acoustic impedance significantly higher than that of the transducer material. The radiating face may be any size from a fraction of a wavelength (in water) to many wavelengths, but difficulties arise when the face dimensions are comparable with the thickness of the crystal, due to interference between different modes of vibration. For simple assemblies, such crystals may be mounted in foam rubber or plastic, to keep the water from the back of the crystal and provide a compliant mounting, but another method, particularly suitable for multi-element arrays, is to mount the crystal on a half-wave passive plate, which can form part of the housing. If the crystal is on the inside, radiating out through the mounting plate, the problem of providing a water-tight, pressure-resisting air backing is neatly solved. One additional advantage is that the thickness of the mounting plate, usually made of a light metal such as aluminium, can be adjusted to vary the resonant frequency, and this is important for multi-element arrays, since the manufacturing tolerances on the crystals themselves is generally too wide. The only serious disadvantage is the decrease in bandwidth, which is of the order of half that for a simple ceramic crystal radiating directly into water.

There are limits on the lowest frequency for which a resonant plate can be made, because of the difficulty in maintaining a sufficient voltage across a thick ceramic plate for poling, and so low-frequency transducers are made by mechanically loading an active element (or a stack of them) with passive head and tail sections, thus making a "sandwich" element, in which the complete assembly resonates in its fundamental half-wave mode. There is much greater freedom of design, as the proportion of active material can be varied and also materials of different acoustic impedances can be used for the loading sections; in this way the effective coupling coefficient and the bandwidth can be tailored for particular applications. For transducers with radiating heads with dimensions less than a wavelength (in water), there is a further degree of freedom offered by the possibility of changing the cross-section; if a large head, shaped so that it behaves as a rigid piston, is mounted on a small crystal stack, the bandwidth is greater than that of a stack with the same size of head and constant cross-section. By this means for example, the Q can be as low as 5, compared with 20 for a straight stack.

Tubes and spheres can also be used as resonant devices, in particular as omnidirectional sources (in a cylindrical or spherical sense), using either the thickness or the circumferential resonance. For very low frequencies, below 1 KHz for example, flexurally vibrating bars can be assembled into barrel-shaped structures, which are used for high-power CW sources.

3.0 Magnetic field systems

3.1 General considerations

The mechanisms used in underwater transducers are summarised in this table :

Type	Category	Frequency	Example
Electrodynamic	Linear	Up to 50 KHz	Moving coil systems
Magnetostrictive	Polarised	" 200 "	Resonant transducers
Dynamometric	Irreversible	L.F. broad band	High intensity

Of these, the magnetostrictive type has the most general use, the other two having limited applications as sources.

3.2 Magnetostrictive transducers

These are most commonly used as resonant transducers; they can be used as broad-band hydrophones below resonance, but the voltage response is proportional to frequency, and this is not as useful as the uniform response which can be obtained from electrostrictive transducers. The material most commonly used is nickel, annealed to give it the required characteristics and rolled out into thin sheets, either flat with slots for the windings and assembled into stacks in a similar way to transformer cores, or sometimes as a long strip wound up into a scroll. The polarising field is usually provided by permanent magnets in slots in the laminations, rather than by direct current in the windings, for better overall efficiency, but it is possible to omit the polarising in a projector and drive it by a unidirectional current pulse, causing it to ring at its natural frequency of mechanical resonance. Ferrites can also be used, but they are less robust than nickel, being weak in tension, and so are less suitable for projectors. It is possible to bond head and tail masses to stacks of laminations, but this is not often done.

Magnetostrictive transducers have one great advantage over electrostrictive types, in that with a winding of insulated wire they need no housing, i.e. they are "free-flooding", though still needing a pressure-release backing for maximum efficiency. On the other hand, the range of shapes and sizes is much more restricted, since tooling-up for stamping out the laminations is more costly and less versatile than for the grinding of ceramic parts. In large quantities they are probably rather cheaper than the ceramic type over the same range of frequencies (approximately 10 to 100 KHz), but at the cost of a lower efficiency and a lower power rating under electrically limiting conditions.

3.3 Other magnetic transducers

Moving coil systems have one application under water, as broad-band non-resonant sources, which are particularly useful at low frequencies, when the dimensions of the source are small fractions of a wavelength and a considerable volumetric displacement may be required. The construction is very similar to a moving-coil loud-speaker, but with a stiff diaphragm of metal, air-backed and with a balancing system to keep the coil central under varying hydrostatic pressure without a stiff mounting. One commercial design has a fairly uniform response from 100 Hz to 5 KHz, and it is useable from 40 Hz to 20 KHz.

The dynamometric device which has some use is the degenerate form (non-polarised) known as the "boomer". This consists of a flat spiral coil, against which is held by a spring an aluminium plate, the other side of which is in contact with the water. A capacitor, charged to a high voltage, is discharged through the coil, the current inducing a current in the plate, which is thereby violently repelled, producing an almost unidirectional pressure pulse in the water with a wide frequency spectrum. For a plate 0.25 sq.m. in area energised by a 1000 joule source, the pulse is about 1 mS. long and equivalent in energy to the detonation of about 1 gm. of TNT. Sources of 10,000 joules and over have also been used.

4.0 Non-electrical sources

Both impulsive and sinusoidal sources can be made. For the latter, hydraulically driven diaphragms can be used, giving powers of several kilowatts at frequencies around 10 KHz and below. For swept-frequency sources, this is a more effective way of obtaining high source levels than by using electro-acoustic devices.

Impulsive sources can be summarised in this table :

Device	Joules/shot	Type	Useful spectrum
High explosive	6.10^6/Kg.	SW & BP	Entire audio
Gas		BP	Low "
Spark	10^5	SW & BP	Entire "
Air-gun	5.10^4	BP	Low "

SW = shock wave, BP = bubble pulse

High explosive is the oldest of these, and it is still important, in spite of the hazards, if very high source levels are required, but for lower levels the alternatives are much preferred. The sparker is included here rather than under the heading of electrical devices, because it depends on the expansion of gas at a small electrode, formed when a charged capacitor is discharged between this one and a larger adjacent electrode, both being in the water. The air-gun is one device which can be made to work without even electrical control; a small volume of highly compressed air is suddenly released into the water through a valve, the operation of which is controlled by a low-pressure air supply operating against a leak from the high pressure side. However electrically triggered versions are more commonly used, as they can be synchronised with other equipment.