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ULTRASONIC PROPERTIES OF PASSIVE MATERIALS FOR TRANSDUCER USE

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INTRODUCTION

This paper describes how to select and design suitable materials for use in high frequency sonar transducers. One type of transducer is shown in figure 1. The piezoelectric element is embedded in a slab of backing material which must be highly attenuating to absorb radiation from the back face and prevent unwanted reflections. It should also have a low acoustic impedance to give high efficiency. The layer on the front of the driving element may simply act as an acoustic window or one or more quarter wave matching layers may be used to broaden the bandwidth of the transducer. In either case the material must have the correct acoustic impedance and have low attenuation.

For deep water use the materials must have good mechanical properties - they must be strong, rigid and able to withstand stress cycles. Low water absorption, creep and corrosion resistance are other considerations.

ACOUSTIC IMPEDANCE OF MATERIALS

The specific acoustic impedance of a material is given by the product of the density and the velocity of sound.

$$Z = \rho c$$

For a slab of material several wavelengths across the velocity of propagation will be the bulk velocity, given by:

$$c_1 = \sqrt{\frac{E(1 - \sigma)}{\rho(1 - 2\sigma)(1 + \sigma)}}$$

E = Young's modulus σ = Poisson's ratio

From a knowledge of the constants ρ, E, σ the velocity and impedance can be approximately calculated. This is useful because acoustic data is not usually given in materials data books. For most materials the velocity does not depend very much on frequency, though this is not so for some of the rubbery materials[1]. The temperature coefficient of velocity[2] can be as large as 0.5% $\deg^{-1}$C for plastics, and much higher at a glass rubber transition point.

The acoustic impedance and velocity for a selection of materials is shown in figure 2. It will be seen that rubbers and plastics all have a low impedance of the same order as water while the metals, ceramics and glasses all have a high impedance. There is a noticable gap in the intermediate range of impedance which can be filled by composite materials.

RUBBERS AND PLASTICS

Rubbers[3] have a low velocity (1000 - 1500ms^{-1}) and density (1 - 1.5 g cm^{-3}). The acoustic impedance is therefore near to that of water and can be made equal to it. The attenuation in some rubbers is low or very low. These materials are used as acoustic windows. Some rubbers have very high attenuation and can be used for acoustic isolation or backing materials.

The room temperature vulcanising (RTV) silicone rubbers are

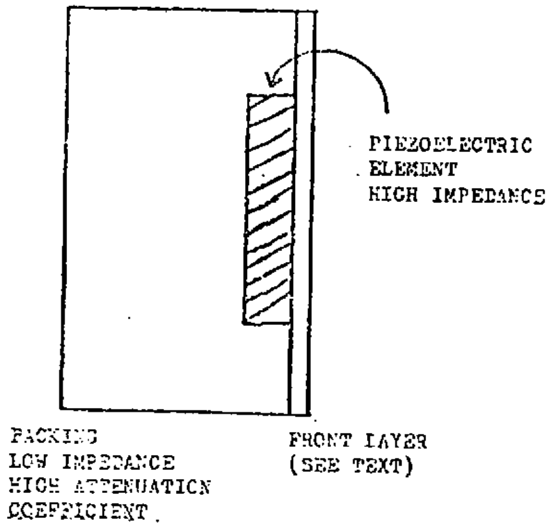

FIGURE 1. The construction of one type of high frequency transducer.

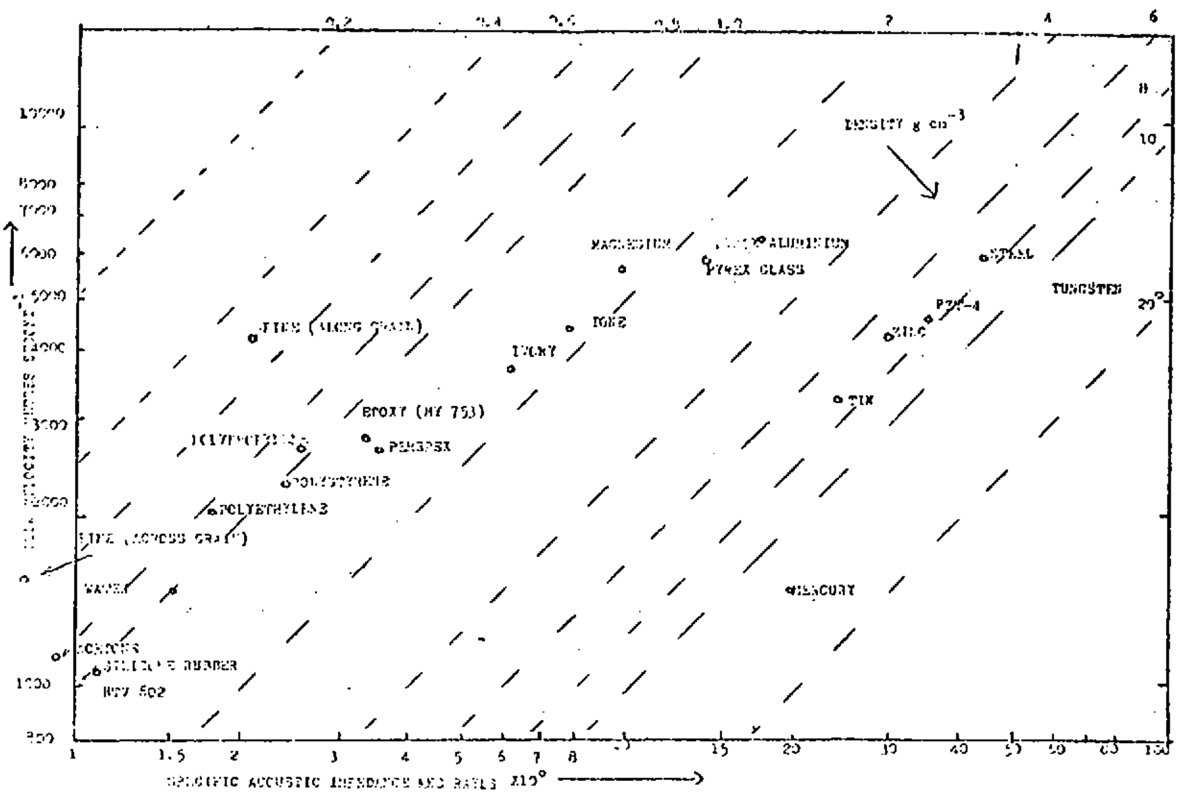

FIGURE 2.
Chart showing the specific acoustic impedance, bulk velocity and density of selected materials.

particularly useful in transducer construction. They have a low viscocity before cure making them easy to mold and have self bonding properties when used with a suitable primer.

Epoxy resins are useful type of rigid material. Most of them have a velocity of about 2500 ms^{-1} and a density of 1.1 - 1.2 g cm^{-3} giving an acoustic impedance twice that of water. Flexible grades may have a rather lower impedance. The attenuation is moderate. The addition of flexibilisers makes epoxies slightly "rubbery" and better able to withstand stress and temperature cycles when bonded to another material. Epoxy materials are useful as front layers for transducers. The layer thickness may be a small fraction of a wavelength, or a quarter or half wave. In selecting an epoxy two practical considerations are the room temperature viscosity and the curing schedule. The ability to harden at room temperature is often an advantage.

ADHESIVES

Transducer construction often requires the use of adhesive joints. All normal adhesives e.g. epoxy, silicone rubber etc. have a rather low acoustic impedance. This means it is difficult to make a good acoustic joint between metal components. For example if two aluminium components ($Z = 17 \times 10^6$ MKS) are bonded with epoxy ($Z = 3 \times 10^6$ MKS) a standard transmission line calculation shows that the adhesive layer thickness must be $\lambda/70$ to reduce the amplitude reflection coefficient to 10%. This corresponds to 40 µm at 1 MHz. The best acoustic performance is given by the thinnest possible bond but considerations of durability may require a thicker bond. The use of filler powders in epoxies to raise the impedance reduces the adhesion. Solders give good joints but are difficult to use with PZT due to the risk of depoling. For these reasons it is best to avoid the use of adhesives and try and "design the bonds out".

COMPOSITE MATERIALS

The impedance of a material may be modified by the use of filler powders. For example the addition of tungsten powder to an epoxy resin increases the density, Young's modulus and slightly reduces Poisson's ratio. The result is that the velocity is reduced and the acoustic impedance increased. Materials of impedances up to 40×10^6 MKS may be made in this way. Applications of this are the fabrication of matching layers and high impedance backings for wideband transducers for non destructive testing and medical use.

A problem with composite materials is inhomogeneity because the particles will settle out, but this can be avoided by slow rotation about a horizontal axis. Another way of overcoming this problem is to make the filler particles close packed. For uniform sized spherical particles the packing factor (the ratio of the volume occupied by the particles to the total volume) is 0.74, but for many powders the factor is rather lower than this. By a suitable choice of filler powder with the right packing factor and density a uniform material of a specified impedance can be made. A disadvantage is that the uncured mixture is rather viscous making it difficult to remove all the entrapped air. The use of a filler powder usually increases the attenuation but if the particle size is much less than a wavelength the scattering is small.

If air is incorporated in a material - foam plastics for example - the acoustic impedance is lowered. This is a useful way of making backing materials because the impedance can be less than that of water giving efficiencies over 50%. Additionally these materials are highly attenuating. However, they are rather soft and not suited to deep water applications.

A much more satisfactory material known as a syntactic foam can be made by the use of thin walled glass balloons. These have time densities as low as 0.2 g cm^{-3}. Using epoxy resin as a matrix material, a material of density down to 0.5 g cm^{-3} with a velocity of 2500 - 3000 ms^{-1} can be made[4]. The impedance is thus similar to water giving a backing of efficiency 50%. These materials are easily molded, rigid and strong. The compressive strength is in excess of 2.1×10^{13} N m^{-2} (3000 psi, equivalent to 2000 m of water).

In making a composite there is a wide choice of matrix materials but for transducer applications epoxy is useful because it is self bonding and does not require the use of adhesive layers.

ATTENUATING MATERIALS

The attenuation of sound in a medium is given by:-

$$A = A_o \exp \quad (-\alpha x)$$

A = amplitude α = attenuation coefficient (nepers per unit length).   x = distance

The attenuation coefficient α for a material at a particular frequency is usually expressed in dB cm^{-1}. At low frequencies the attenuation is often expressed in terms of a loss tangent ($\tan \delta$) or quality factor (Q) which is related to α as shown:

$$\alpha \text{ dB cm}^{-1} = (273 \ f)/(Q \times c)$$

$$\tan \delta \simeq Q^{-1}$$

f = frequency MHz   c = velocity of sound mm μs^{-1}

In discussing attenuation the frequency dependence of α is particularly important. For many solid materials, in the absence of relaxation effects and scattering, the attenuation per wavelength or the quality factor (Q) is largely independent of frequency. This means that the attenuation per unit length (dB cm^{-1}) is approximately proportional to the frequency.

$$\alpha \propto f$$

This is an extremely useful rule of thumb. In many other circumstances the attenuation may be expressed as

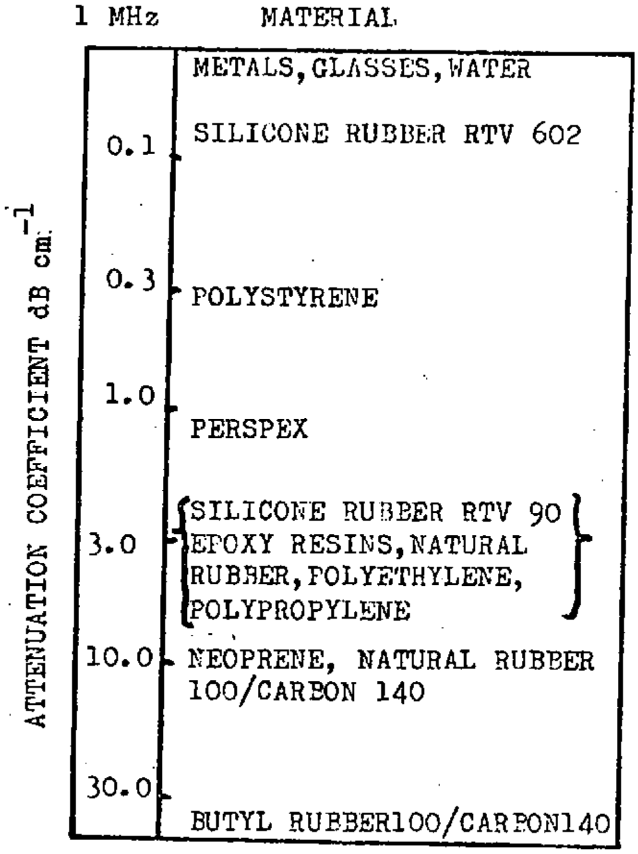

FIGURE 3. Attenuation coefficients of some materials.

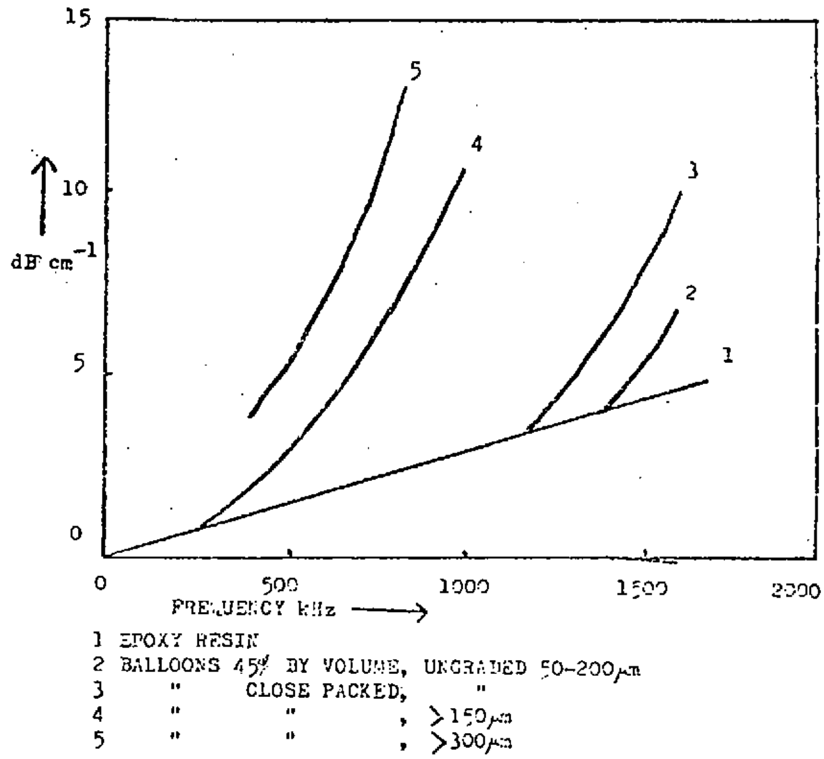

FIGURE 4. Attenuation coefficients of some epoxy resin - glass balloon composites.

$$\alpha \propto f^n$$

For liquids n = 2 due to the property of viscosity. For scattering materials n = 4 in the Rayleigh region though in practice n usually lies between 2 and 4.

The wide range of attenuation coefficients exhibited by materials is shown in figure 3. Metals, glasses and ceramics all have low attenuation coefficients but scattering can become important in the MHz region. Plastics and rubbers have rather higher attenuation.

For transducer backings highly attenuating materials are required. Single component materials with the exception of some of the rubbers are not sufficiently attenuating. Consider a material of velocity 2500 ms^{-1}. The wavelength at 500 kHz is 5 mm. To achieve an attenuation of 5 dB cm^{-1} the attenuation per wavelength must be 2.5 dB and Q = 11. Most materials do not have a Q anything like as low as this, but a low velocity is favorable because the backing will then contain more wavelengths. This feature is partly responsible for the high attenuation of some of the rubbers. Attenuation or energy loss in a material can arise in a number of ways. The presence of foreign atoms in a metal can cause relaxation peaks - this is the mechanism of the high damping alloys - but the effect is not large enough to be useful. In plastics and rubbers the motion of side chains under stress causes energy loss. Of the common plastics polyethylene has the greatest attenuation coefficient and of the rubbers butyl is the best. An important feature is that attenuation is usually rather sensitive to temperature (normally it increases with temperature).

To achieve very high attenuation one has to resort to composite materials. The addition of a filler gives two additional sources of attenuation - sliding between the filler and matrix, and scattering. The second effect is very frequency dependent but the first is less so. The addition of fine carbon powders to rubbers can increase the attenuation coefficient by up to 200%. Butyl rubber with 30% by weight of carbon has an attenuation coefficient of 40 dB cm^{-1} at 1 MHz. In non rubbery materials the sliding effect is much less strong[5].

The use of the scattering mechanism can give very high attenuation. The attenuation coefficient due to scattering can be simply expressed as:

$$\alpha_s = N\, d^6\, S/\lambda^4$$

$$\alpha_s \propto d^3\, S/\lambda^4 \qquad \text{for close packed particles}$$

N = no. of filler particles per unit volume

d = particle diameter $\ll \lambda$ (Rayleigh region)

λ = wavelength

S = scattering factor

The magnitude of the scattering factor S depends on the relative difference in density and elastic properties of the filler and matrix. Foam and systactic foam rubber materials have very high attenuation coefficients because the scattering factor is high. Attenuation coefficients of 40 dB cm^{-1} at 500 kHz can easily be achieved. For the rigid plastics the scattering factor is not as high and the diameter of the filler has to be an appreciable fraction of a wavelength. A useful material for transducer backing is a mixture of epoxy resin and glass balloons. Figure 4 shows the attenuation factor for some test samples of these materials.

All composite materials will show scattering behaviour at sufficiently high frequencies. When using fillers to modify the impedance of a material the particle size must be small enough to prevent this occurrence.

CONCLUSION

It is possible to fabricate suitable materials with the correct properties for most transducer applications. Impedance, velocity and attenuation may be adjusted by the correct choice of matrix and filler. Composite materials can be designed[4] to an approximate specification from a knowledge of the properties of the components. The exact specification is achieved through experimental adjustment. The design and application of anisotropic materials is a promising but largely empirical study at present.

ACKNOWLEDGEMENT

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