ACOUSTICS AND THE PROPERTIES OF MATERIALS*

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A brief survey is given of material properties associated with dynamic
deformation of matter and of the possibilities of designing materials to satisfy
certain acoustical and mechanical criteria.

1. Introduction

The purpose of this paper is to collect together in perspective the existing
knowledge of material properties which are involved in the study of acoustics,
and so our concern is essentially related with the dynamic properties of a medium.
However, these properties can be affected by external agencies through the
coupling of electrical, magnetic, electromagnetic or thermal phenomena with
the mechanical properties, so that in considering any particular acoustical
property care has to be taken in defining the measuring conditions. For example
a piezoelectric medium can be stiffened by the application of an electric field so
that the velocity of a surface wave will be different in the cases when the medium
is or is not subjected to an electric field.

The primary interest in the acoustic properties of materials until the last
few decades has been in their use to minimize the effect of airborne sound
and structure-borne vibration on comfort and working efficiency in our everyday
life and to provide appropriate conditions for the hearing of speech and music.
The increasing industrial and medical use of ultrasound, however, has created
an inevitable interest in the behaviour of materials at the higher frequencies.
At the kernel of such an activity is the piezoelectric transducer and its mechani-
cal properties, and those of the coupling medium to the system under investi-
gations are of vital concern. The bonding medium must possess the optimum
acoustical properties for the transmission of the maximum acoustical power

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from the transducer to the test medium and additionally must possess adequate mechanical strength to withstand the applied alternating stresses and temperature cycles. The development of space research has increased the upper limits of the working temperatures required of vibrational-isolating materials and also the need for their mechanical stability at the very high sound pressure levels, i.e. 160 dB or greater, created by rocket engines.

The theoretical understanding of the dynamic mechanical properties of materials may be discussed either phenomenologically or from the atomic or molecular aspect and both points of view are completely understandable only within the range of perfect elasticity, i.e. the material obeys Hooke's law, stress and strain are time independent and strain is completely and instantaneously recoverable upon the release of load. Elasticity theory enables the medium to be completely characterized by a set of elastic moduli to give a satisfactory phenomenological interpretation.

The theoretical calculation of the elastic constants of metals and of ionic crystals from interatomic forces has been carried out and good agreement obtained with experiment only for the simpler solids, but it would seem that the difficulties are of technique and not of principle. More complex are time-dependent phenomena, anelasticity in metals and viscoelasticity in organic materials and glasses, and we are concerned here with stress relaxation, creep and internal friction at very low stresses. It should be stated that the nonlinearity of the stress-strain curves (shear) due to time effects must be distinguished from an inherent non-linearity of stress to strain. Phenomenological theory in the anelastic range appears satisfactory but there is a great difficulty in relating anelastic properties to interatomic forces.

A great deal of progress has been made in relating the viscoelastic properties of polymers to chemical structure, to molecular configuration and to the formation and breaking of bonds and, likewise, the anelastic properties of glass are reasonably understood. Rubber behaves rather uniquely and is described quite successfully by a statistical theory which depends on the analysis of the configurational response of a series of mesh points connected by flexible chains of varying length.

The significant characteristics of the plasticity behaviour of solids is the inherent non-linearity of the shear stress to shear strain together with the large permanent deformations. The time-dependent phenomena of creep and stress-relaxation in the plastic region are time-wise similar to viscoelastic behaviour but not with respect to stress. Large applied stresses often result in a permanent change of material properties referred to as strain or work hardening. The yield stress observed is much lower than theoretically predicted from the forces concerned in the slip and glide of a perfect crystal, and by way of explanation of this divergence the concept of dislocations was proposed and has been used to correlate a number of mechanical properties, although limited in its quantitative aspect. Fracture and strength of a material are probably those mechanical

properties about which we have least understanding and it is uncertain whether strength can be described in terms of a true material constant, while fracture is a complicated phenomenon as various processes could lead to disintegration [1].

The liquid state has received less theoretical attention than that of solids as regards structural aspects but there is an increasing interest academically and in industrial and medical applications. The use of sonar and underwater communications in general require a knowledge of the ocean path as regards depth, salinity and temperature pattern, and internal waves could play the part of dislocations in solids and influence beam scattering. A brief mention is only possible of the significance of acoustics in liquid structure. Of all pure liquids only ordinary and heavy water has a positive velocity temperature coefficient, dV/dT, at ordinary temperatures, but at 74°C the coefficient has decreased to zero and subsequently becomes negative as for other liquids. This anomalous behaviour is explained as due to the dual presence of a non-associated and close packed form and to an associated form or cluster. According to HALL [2] the compressibility of the latter under acoustic compression is mainly due to the breaking of the hydrogen bonds creating a partial destruction of the associated bulk structure while the compression of the free-space amongst the non-associated water molecules gives the second contribution to the compressibility. On raising the temperature the structural component of the compressibility decreases due to the falling fraction occupied by the cluster state but the other compressibility rises due to increasing inter-distance between molecules, thus leading to a compressibility minimum while at a slightly different temperature a maximum occurs in the sound velocity. Similar cluster phenomena have been observed by LEE KIN TAT [3] in ultrasonic measurements with liquid mercury amalgams (Fig. 1). Air bubbles in water increase the com-
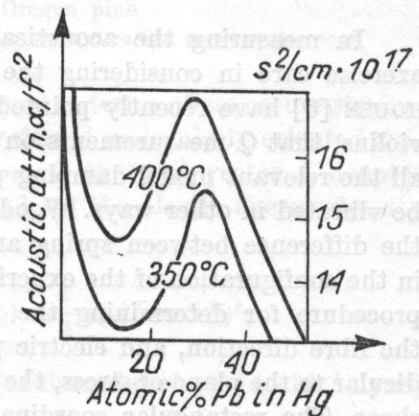
Fig. 1. Cluster phenomena observed in ultrasonic measurements with liquid mercury amalgams

pressibility [5] so that at 50 % concentration the sound velocity reaches a minimum value of 20 ms⁻¹ (Fig. 2).

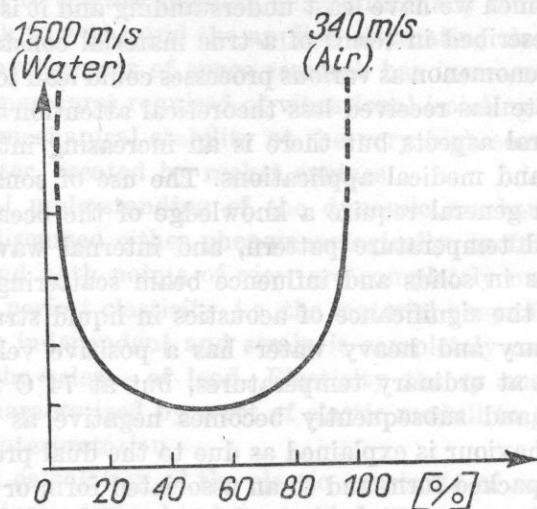Acoustic relaxation phenomena occur in all forms of matter and the mole-

Fig. 2. Velocity of sound in water containing bubbles (after KARPLUS)

cular interaction of oxygen and water vapour is an interesting illustration. The resulting acoustic damping, due to this cause, begins to strongly complete, at around 4 kHz, with the wall and audience absorption in a concert hall. The effect has to be taken into account in experimental acoustic model simulation of auditoria [1, 4].

2. Some experimental considerations

In measuring the acoustical parameters of materials it is necessary to exercise care in considering the geometrical aspects. McINTYRE and WOOD-HOUSE [6] have recently pointed out, in connection with the construction of violins, that Q measurements on bars are not sufficient by themselves to give all the relevant model damping properties of an isotropic material which is to be vibrated in other ways. Wood is anisotropic and also inhomogeneous due to the difference between spring and summer growths, so care has to be taken in the configuration of the experimental specimen. Fig. 3 indicates the general procedure for determining the piezoelectric polarisation where the z-axis is the fibre direction, and electric polarisation takes place in a direction perpendicular to the plane of stress, the sign reversing with the direction of the applied shear. The rectangular coordinates assigned to wood structure are shown in Fig. 3, where x is the radial and y is the tangential direction in tree trunk. The anisotropy of Oregon pine is shown in Fig. 4. Nematic liquid crystals contain unique mobile filaments, so-called *disinclinations* (cf. dislocations of a solid), and optically behave as a uniaxial medium with a centre of symmetry,
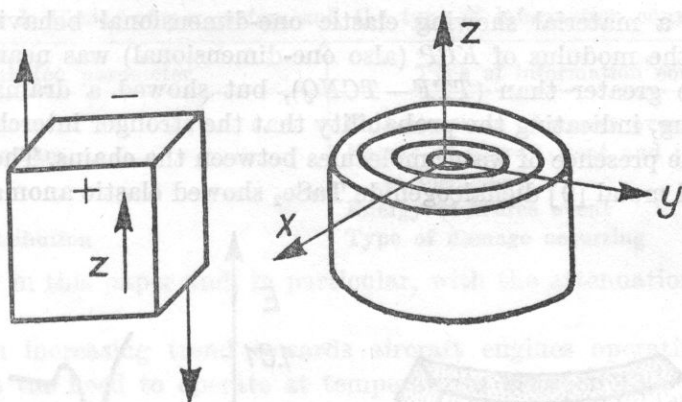
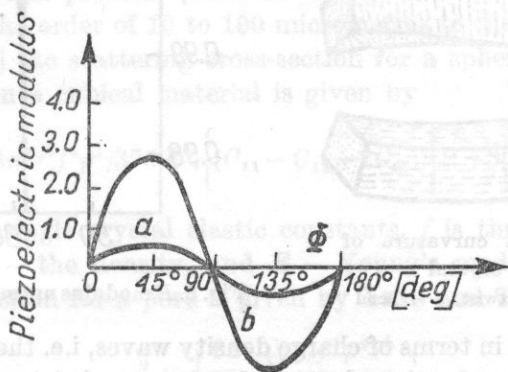Fig. 3. Piezoelectric polarization rectangular coordinates for wood

Fig. 4. The anisotropy of Oregon pine
a — spring growth, b — summer growth, Φ is the angle between fibre and pressure directions

so the piezoelectric properties have to be explained in terms of curvature strains. These arise from the spatial variation of the preferred molecularly oriented axis and its departure from its equilibrium position. If the unit vector L denotes the molecular orientation at any point, then [7, 8] the elastic energy density of a deformed nematic is

$$E = \frac{1}{2} k_{11} (\operatorname{div} L)^2 + \frac{1}{2} k_{22} (L \operatorname{curl} L) + \frac{1}{2} k_{33} (L \operatorname{curl} L)^2,$$

where k_{11}, k_{22} and k_{33} are the elastic constants (of the order of 10^{-5} to 10^{-6} dyne) of splay, twist and bend, respectively (Fig. 5).

Because of the difficulty of preparing one- and two-dimensional compounds in bulk, BARMATZ employed the vibrating reed technique for determining their elastic constants. The low Young's modulus measured for the one-dimensional $(TTF - TCNQ)$ system is consistent with the concept of weak interchain coupling

expected for a material showing elastic one-dimensional behaviour. On the
other hand, the modulus of KCP (also one-dimensional) was nearly one order
of magnitude greater than $(TTF - TCNQ)$, but showed a dramatic decrease
on dehydrating, indicating the probability that the stronger interchain coupling
arose from the presence of water molecules between the chains. The two-dimen-
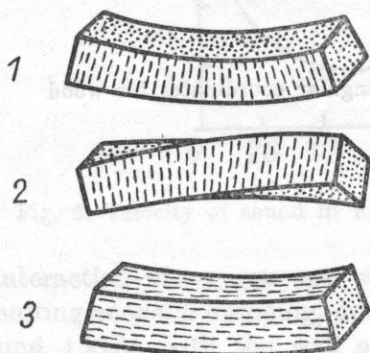sional layered metal [9] dichalcogenide $TaSe_2$ showed elastic anomalies (Fig. 6),

Fig. 5. Distinct curvature of a
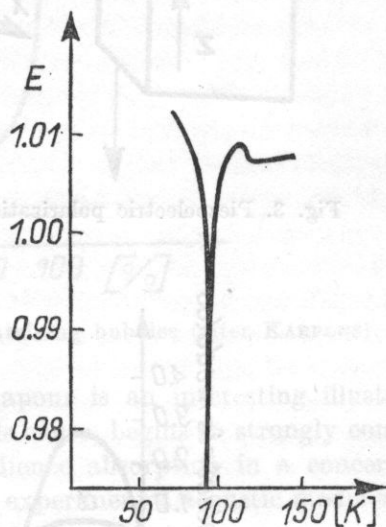liquid crystal
1 — splay, 2 — twist, 3 — bend

Fig. 6. E modulus normalized to E_{3000K}

which were explained in terms of charge density waves, i.e. the periodic variation
of the amplitude of conduction electron density coupled to a lattice distortion
of the same period.

It is significant to point out that ultrasonic, i.e. dynamic, methods of meas-
urement are made in such short cycling times that negligible creep or plastic
strain can occur, which is particularly advantageous for high temperature
experiments. However, from an engineering point of view, care has to be exer-
cised in using the data since usually only very small strain amplitudes are em-
ployed.

The choice of experimental parameters to be used determines the type of
information conveyed as exemplified by those relating to acoustic emission
signals [10] as given in Table 1.

3. Ultrasonic attenuation in solids

Ultrasonic propagation in crystalline solids may be conveniently divided
into two groups, the intrinsic — which is inherent in all solids and involves inter-
action with phonons and with conduction electrons, and the extrinsic mechanism
involving interaction with material defects. It is essentially with the latter that

Table 1. Choice of parameters and the type of information conveyed

Emission parameter	Type of information conveyed
Waveform	Fine structure of source event
Frequency spectrum	Nature of source event and integrity of specimen
Amplitude	Energy of source event
Amplitude distribution	Type of damage occurring

we deal with in this paper and, in particular, with the attenuation in ceramics [11, 12].

With an increasing trend towards aircraft engines operating at higher temperatures the need to operate at temperatures between 1300° and 1400°C demands use of ceramic materials such as silicon nitride or carbide, which possess high strength and thermal shock resistance and also good resistance against oxidation. The problem posed to the acoustics $N.D.T.$ operator is how to test defects of the order of 10 to 100 micrometres in the ceramics. According to PAPADAKIS [13] the scattering cross-section for a spherical cross-section for a spherical grain in a cubical material is given by

$$\beta = (8\pi^2 r^6 f^4 p^2 / 375\, E^4)\left\{(C_{11} - C_{12} - 2C_{44})^2\left[2 + 3\left(\frac{E}{\mu}\right)^{5/2}\right]\right\},$$

where C_{ij} are the single crystal elastic constants, f is the frequency, μ — the shear modulus, p — the density, and E — Young's modulus. The equivalent scattering cross-section for a pore is given by YING and TRUELL [14] as

$$\beta = \left(\frac{64}{9}\pi^5\right)\frac{g_c f^4 p^2 r^6}{E^2},$$

where g_c is a function of the elastic properties of the material and has typically values between 5 and 30. It is evident that there is a very strong dependence of attenuation in ceramics on grain or pore radius (r) so that the scattering will be dominated by the very large value extreme of the grain or pore size distributions. In comparing pores and grains of equivalent size it is seen from the equations that porosity is likely to be a dominating source of attenuation, also the high modulus and low density of the majority of ceramics help to moderate the attenuation problem. The experiments carried out by TITTMANN [15] on fine grained and fully dense Si_3N_4 and SiC indicate that the attenuation is still acceptable at frequencies up to 400 MHz and the frequency dependence is generally smaller than the f^4 relation of Rayleigh scattering.

4. Shock waves in solids

This work has so far been concerned essentially with low intensity sound waves but the changed character of the propagation and the response of the

medium have long been utilised for investigating molecular phenomena in gases [1]. The generation of shocks in solids, except for some polymeric media [16], requires necessarily the detonation of an explosive in contact with it or the impact of a projectile on its surface. The step-pressure pulse generated changes shape during propagation as a result of inertial forces derived from the mechanical properties of the medium and these changes have to be interpreted in terms of the properties, analogous somewhat to the use of an electrical pulse to determine the parameters of an electrical network. The use of plane-wave loading simplifies the interpretation of observations, for there is the possibility of phase transformations in the solid also being induced by shock waves, and it was Johnson et al. [17] whose shock experiments first revealed a triple point in the pressure-temperature phase diagrams of iron (Fig. 7).
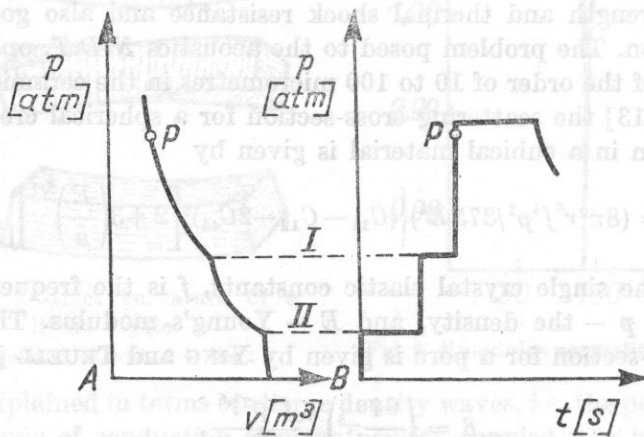

Fig. 7. A — Hugoniot curve, B — pressure time curve for material shock-excited
to pressure P
I — phase transition, II — elastic limit

5. Design of materials

A knowledge of the detailed effects of structural factors upon physical properties can often enable materials to be designed to satisfy particular acoustical requirements, and in Table 2 some possible means are given, whereby temporary or permanent changes can be brought about in the normal behaviour of a material.

As pointed out recently by WIRT [34] bulk absorbing materials are not very suitable, for example in aircraft, with its specific constraints of high temperature, vibration and space. He has suggested new forms of sound absorbing structure employing a number of acoustical elements in both parallel and series. Amongst the various new materials that offer exciting possibilities let us mention metallic glasses which are effectively metals in which the atoms have the random structure of a liquid but retain the close packing of a solid. They are

generally extremely hard with tensile strengths greater than good stainless steels. The absence of grain boundaries is evident in their low ultrasonic attenuation [35].

Table 2. Means of bringing about changes in behaviour of a material

| Process or agency	Application
Stressing of solid	Hardening of material (increase of elastic modulus), also inducement of residual compressive stresses for alleviation of fretting fatigue [1]
Nuclear irradiation	Gamma irradiation of polyethylene changes structure to rubbery and, with increased dosage, to brittle solid [18, 19]
Ion implantation	Applied to surface wave devices crystalline structure is disturbed and causes velocity change, of opposite sign in quartz and lithium niobate (Fig. 8) [20, 21]
Varying crystal growth rate	Control of Q of synthetic quartz crystal (Fig. 9) [22]
Use of external agencies	Illumination of acoustic amplifier semi-conductor to control electron velocity. Modifying acoustic propagation in liquid crystal by applied electric field [23]
Temperature variation	Changes velocity, acoustic impedance etc. Utilised in BELL's acoustic thermometer [24]
Compounding of media	Carbon fibres in plastic change acoustic character as well as mechanical strength and density. Also use of Cork particles in rubber isolator [26, 25] (Fig. 10)
Introduction of a second phase	Varying carbon content in steel alters acoustic damping. Damping in water also increased by presence of salts [27, 28]
Graded material	In absorbers for underwater use the medium is modified in a gradual manner through its thickness, e.g. by mixing a rubberlike material with fillers like graphite and air-containing substances like sawdust [29]
Monomolecular layers	Formation on liquid surfaces leads to increased damping of surface waves [30]
By change of material geometry	The addition of ribs to vibration isolators increases their stiffness. Also compounding of vibration absorption mountings. Use of wedges in anechoic rooms [32]. Rubber tubing containing air for pressure release absorbers [33, 31]
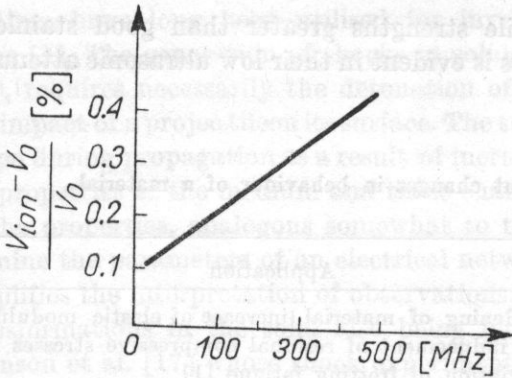
Fig. 8. He and Li ions in quartz
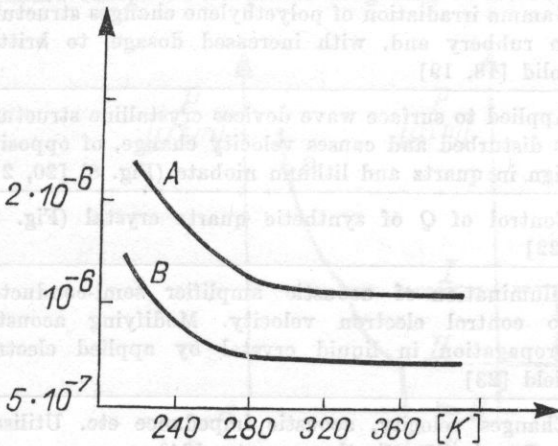
Fig. 9. Q^{-1} of synthetic quartz and growth rate

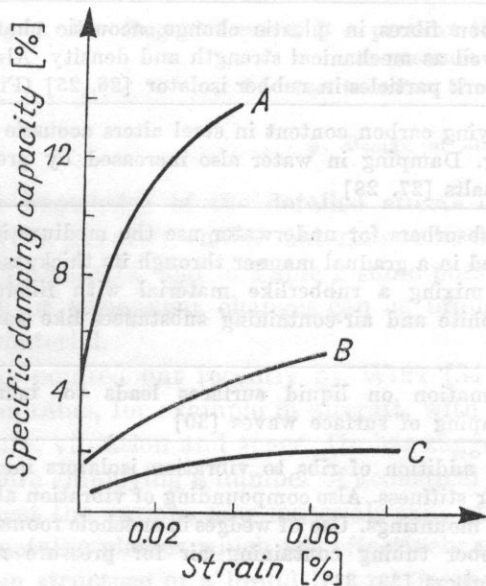curve A — 0.55 mm per day, curve B — 0.25 mm per day (JONES and BROWN)

Fig. 10. Damping in cast irons (FOX and ADAMS)

A — coarse flake graphite, B — fine flake graphite, C — modular graphite

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