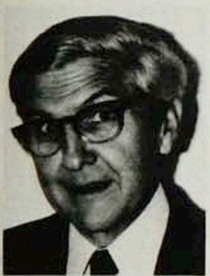
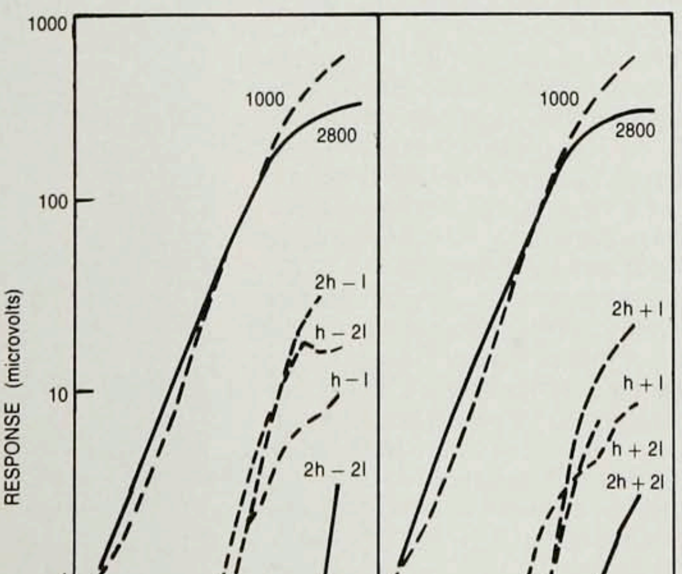
A new wave of acoustics

Robert Beyer



Robert Beyer, a professor of physics at Brown University, is a past president of the Acoustical Society of America. He is the current Chairman of the International Committee on Acoustics.

In 1946, Richard Feynman, giving a contributed paper at a meeting of the American Physical Society, remarked that the allotted time was not long enough for him to read his abstract (it was a peculiarly long one), but only enough for him to point out the errors in it. In a similar vein, modern acoustics is so broad that the space allowed here is scarcely enough to reprint the PACS classification of the subject, let alone to instruct or entertain. Acoustics today is a festival of the applications of physics, both theoretical and experimental. We must therefore restrict ourselves to a sampling of topics, ranging from acoustical devices as ancient as the guinea pig's ear (figure 1) to others as modern as the electron-acoustic microscopic (figure 2).



***Responses** of a guinea pig ear. Difference (left) and summation (right) tones produced by stimulation at 1000Hz (l) and 2800 (h). Responses are shown for primaries (l,h) and various combinations. (From Wever and Lawrence.)* *Figure 1*

Hearing

In sensing the waves of acoustics that have been generated during the past fifty years, it is perhaps appropriate to begin with the oldest of all acoustical receivers—the ear. That the subject of the ear is not a completed study is evidenced by the award of the Nobel Prize in Physiology or Medicine to Georg von Békésy in 1962 "for his discoveries concerning the physical mechanism of stimulation within the cochlea." Von Békésy was a physicist who began his career with the Hungarian telephone company and finished it in the Harvard psychology department. He attempted to understand the coupling of the telephone system with the human ear. This led him to delve into the operation of the ear itself, and to create numerous mechanical and electrical models of the ear, and more especially of the cochlea.

The classical hearing theory of Hermann von Helmholtz had, as a fundamental tenet, the idea that the cochlea operated as a perfectly linear system. The cochlea is itself divided by a membrane known as the heliocotrema, with liquid filling both sides of the chamber. Von Békésy presented a theory of the stimulation of hearing by surface waves that travel along the interface between the cochlear fluid and the heliocotrema. These waves generate eddies in the liquid (von Békésy eddies). Modern analysis has demonstrated that these surface waves travel, like all shallow liquid-

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surface waves, with a velocity that depends on the ratio of the depth to the wavelength. Thus the wave propagation is inherently nonlinear.[1]

This nonlinearity leads to many complicating features of the hearing process, but we shall be interested here in only one: The nonlinearity of wave propagation in the cochlea provides an explanation for the "Tartini tones," a hearing phenomenon pointed out by the famous 18-th century violinist, Giuseppe Tartini, who noted that when two notes were sounded simultaneously (and loudly) on his violin, he could hear the difference tone. More than a century later, Helmholtz noted that he could also hear the sum of the two tones. If the response of the ear were strictly linear, one would not hear such combination tones. Such nonlinear phenomena were subsequently studied in great detail by Glenn Wever and Merle Lawrence. Working with animal ears about 40 years ago, they established the fact that virtually any linear combinations $m f_1 \pm n f_2$ of two frequencies f_1 and f_2 (m, n integers) could be detected in the electric response of the ear (figure 1).

Nonlinear representations

Thus acoustical nonlinearity clearly exists within the ear. It took a somewhat longer time for the acousticians to accept the fact that it exists outside the ear also, although nonlinear mathematical representations of sound waves of small but finite amplitude were made by Siméon Poisson, and later by Bernhard Riemann more than one hundred years ago.[2] In 1860 Samuel Earnshaw developed an implicit expression connecting the acoustic displacement velocity with distance and time. Earnshaw's solution was not obtained in explicit form until 1935 (by Eugenio Fubini), and even then, Fubini's work remained almost unnoticed until the late 1950s.

The governing equation for the particle displacement ξ in a plane wave, in a gas with small-amplitude sound speed c_0 and ratio of specific heats γ, is given by

$$\ddot{\xi} = \frac{c_0^{\,2}}{[1 + \partial\xi/\partial x]^{\gamma+1}} \frac{\partial^2 \xi}{\partial x^2} \qquad (1)$$

where all dissipation effects have been neglected.

Note in equation 1 that the effective sound speed, for given $\partial\xi/\partial x$, is equal to the square root of the factor multiplying the second space derivative. If we introduce the condensation $s = (\rho - \rho_0)/\rho_0 \simeq -\partial\xi/\partial x$, where ρ and ρ_0 are the instantaneous and mean densities of the fluid, then the effective sound speed for the portion of the disturbance having the condensation s will be, to first order,

$$v \simeq c_0[1 + (\gamma + 1)s/2] \qquad (2)$$

The points in the wave where the gas is more condensed will therefore travel at higher speeds than those at which it is more rarefied. Hence the density crests tend to overtake the density troughs, and shock-wave conditions are approached.

In the case of a liquid, we can replace the familiar isentropic relation of a gas, $pv^{\gamma} =$ constant, with

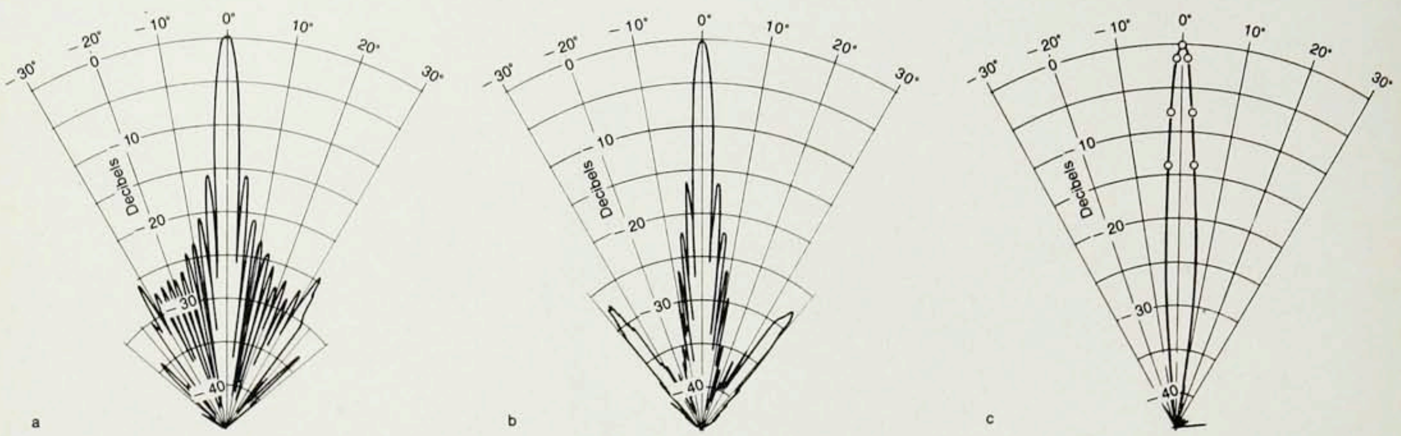
$$p = p_0 + As + \tfrac{1}{2}Bs^2 + \dots \qquad (3)$$

where $A = \rho_0 c_0^{\,2}$ and $B = \rho_0^{\,2}(\partial^2 p/\partial\rho^2)_{s,\rho_0}$. The ratio of specific heats, γ, will then be replaced (correct to terms of second order in s) by $B/A + 1$.

Equation 1 was the one solved implicitly by Earnshaw in 1860 and solved again by Fubini in 1935. Using Fubini's solution one can show that a simple monochromatic wave passing through a medium will distort, producing more and more of its harmonics. The amount of the distortion increases with the distance, the initial intensity and the magnitude of γ (or B/A). The presence of dissipation will of course hinder the distortion, but a weak shock or near shock wave can easily be obtained in fluids and even in solids.

The search for a more effective solution of the dissipative case led a number of workers, especially Rem Khokhlov and his Soviet colleagues, to force the actual equation of motion into the form known as Burger's equation. As one of the first acoustical users of Burger's equation, J. S. Mendousse, described it,[3]

Acoustical interference pattern *on a metal disk excited by the chopped electron beam of an electron–acoustic microscope. (From G. Slade Cargill. See PHYSICS TODAY, October 1981, page 27.) Figure 2*



"One imagines an observer moving with the average velocity c, riding the wave, so to speak; and one assumes that only slow changes occur in the state of the medium near this observer. In a suitable system of coordinates, some of the particle derivatives are then very small and can be neglected in many places where they occur."

One can therefore recast the equation in the following nondimensional form

$$\frac{\partial W}{\partial \sigma} - W\frac{\partial W}{\partial y} = \frac{1}{\Gamma}\frac{\partial^2 W}{\partial y^2} \qquad (4)$$

where W is the particle velocity, σ the spatial coordinate and y the reduced time $[y = \omega(t - x/c)]$. The parameter Γ is a characteristic quantity, sometimes called the Goldberg number, incorporating various thermodynamic parameters. Equation 4 can be solved in exact form.

Because the medium is effectively a nonlinear device, the simultaneous transmission of two plane waves of different frequencies in the same direction will lead to the production of sum and difference frequencies, much as they are produced in the ear in the case of Tartini tones. It was noted by my Brown colleague Peter Westervelt in 1957 (arguing from Sir James Lighthill's analysis of the acoustics of a turbulent medium) that the difference frequency had some highly favorable properties in underwater sound signaling. This difference frequency—given the name parametric array by Westervelt—has the narrowness of a beam corresponding to the primary frequency; it is far narrower than what one gets from a transducer of the same size operating at the low frequency. At the same time, the low-frequency component would have the dissipation characteristics of the difference frequency; it has far less attenuation than the primary signal. Such a parametric-array sonar has already found its practical applications (figure 3).

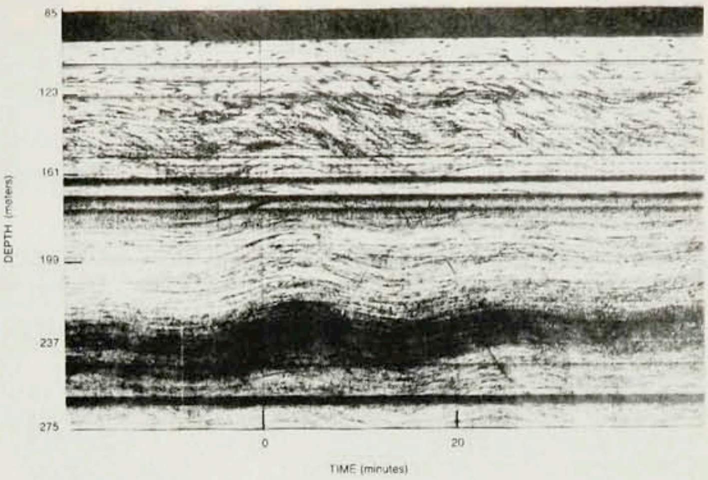
Underwater sound

Parametric-array sonar is of course one small item in an enormous field of acoustics—underwater sound. The development of submarine signaling by Paul Langevin in France during World War I, and the widespread application of quartz crystals by Walter Cady and others had put sonar detection of underwater obstacles on a firm footing by World War II. Since then, a steady improvement in the quality of electronic equipment, better signal processing and detailed studies of sound propagation in inhomogeneous media have led to great improvements in the ability of sonar (both passive and active) to detect, delineate and monitor underwater targets. The discovery of the SOFAR channel in deep ocean water during World War II, where a minimum in the sound velocity makes the geometric spreading two-dimensional (inverse first power of the distance), has led to the development of signaling in the ocean over ranges measured in thousands of kilometer. As we shall see later, this has also led to an improvement in our knowledge of a fundamental physical parameter—the absorption of sound in the ocean at low audio frequencies.

It has long been known that sound waves in the ocean are subject to fading, but only in recent years has the basic cause of this effect been well understood and its magnitude properly calculated. Just as transverse water waves can propagate on the surface of the ocean, so also can volume gravity waves—the so called internal waves—propagate beneath the surface. These waves are most pronounced in regions where the density of the water changes very rapidly with depth, or where there are two water masses of different density (because of different salinity, for example).

Benjamin Franklin noted in 1762 that the natural periods of the common surface of two liquids of very nearly equal density are very long compared with those of a free surface of similar extent. Other observers noted the "dead water" of a boundary between two layers. Thus, if the hull of a ship passes through such a boundary, it excites something like surface waves at the interface, hindering the motion of the vessel. These were early observations of internal waves, which may have amplitudes in the tens of meters and which may propagate over great distances. Any sound wave passing through such a wave will experience local, periodic changes in the properties of the medium (density, temperature and so forth), all of which have an effect on the re-

***Directivity patterns** in parametric-array sonar. Beam pattern of a 418-kHz carrier (a) and a 482-kHz carrier (b). The theoretical and experimental beam pattern of the difference frequency is shown in (c). (From T. G. Muir,* An Analysis of the Parametric Acoustic Array for Spherical Wave Fields, *Applied Physics Labs, University of Texas, Austin (1971).)* *Figure 3*



***Internal waves in the ocean.** (Courtesy of F. H. Fisher, Marine Physical Laboratory, University of California, San Diego.)* *Figure 4*

fraction of the sound beam. Thus the signal will move in and out of regions of different sound velocity and the signal arriving at a fixed receiving point will fluctuate in time. A sample of such fluctuations is shown in figure 4. The concerted attack in the 1970s by a number of scientists not generally known as acousticians (Roger Dashen, Freeman Dyson, William Zachariasen, for example) has led to a satisfactory understanding of these fluctuations, in which the spectra to be expected from a given variety of internal wave perturbation can be determined and compared favorably with experiment.[4]

Another important problem of underwater sound has been the theoretical and experimental study of the scattering of acoustical waves from various obstacles. In the 1950s and '60s, Robert Hickling and others analyzed the reflected signal to be expected from the incidence of a plane, monochromatic wave on an elastic sphere. The connection of these results with the actual time series describing an acoustic pulse has led Larry Flax, Werner Neubauer and others to carry out fast Fourier transforms of both incident and scattered signals, to obtain characteristic form factors for scattering from individual targets.[5] This analysis has been extensive and is still in progress. There is considerable hope that one can achieve effective particle identification, not only for spheres of the size of underwater mines, but also for the detection of minute particles or bubbles in various flow systems.

The unity of acoustics can be seen in the fact that we can transfer immediately from the search for underwater obstacles of the size of mines and submarines to the detection of bubbles in blood and micron-size impurities in industrial flow systems. When a pulse of ultrasound with a frequency in the region of 5 MHz is incident on a particle or bubble in a liquid medium, energy will be scattered in all directions, but the greatest scatter is in the backward direction. This being a case of Rayleigh scattering, the scattered signal is proportional to the fourth power of the frequency. Thus the detection of the particle or bubble can be performed even at bubble diameters substantially smaller than the wavelength.

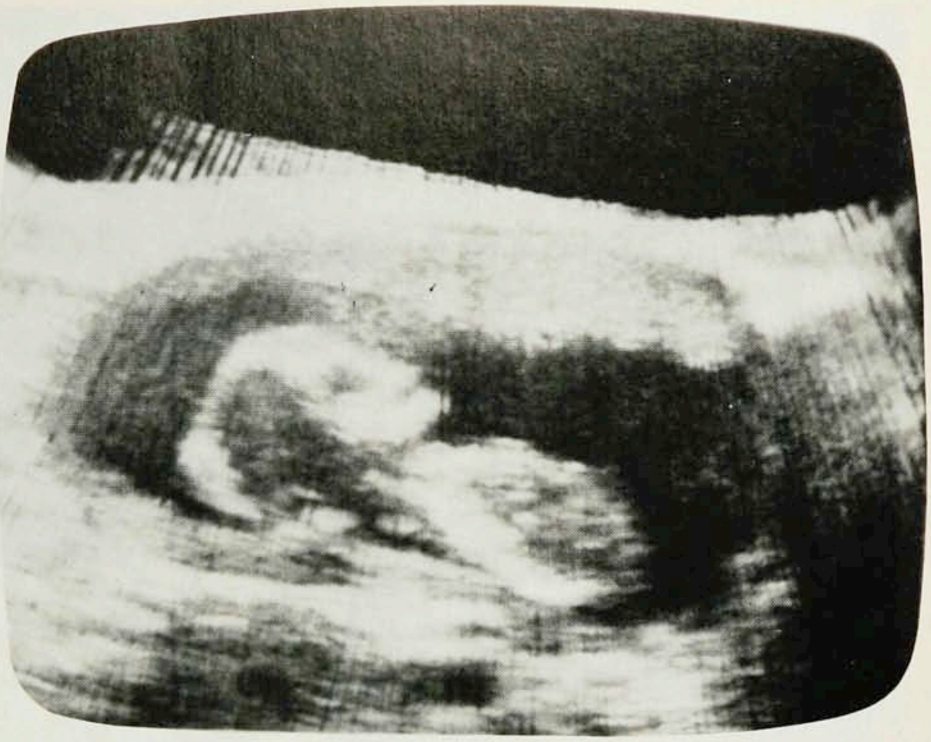
Acoustical diagnostics

The reflection or backscattering of sound from defects in solids gave rise to a class of industrially useful diagnostic techniques known as non-destructive testing in the 1930s and 40s. This same appellation, one hopes, may be applied also to the examination of the human interior by means of ultrasonics! Considerable research has been carried out on the possible side effects of ultrasound on human tissue; but in all cases studied, the level of ultrasound used has been insufficient to cause any tissue damage. It has therefore become quite widely used, especially in fetal scans (figure 5) and the imaging of various internal organs, where much detailed information can be obtained in a relatively simple manner.

A somewhat different use of the scattered ultrasound is involved in echocardiography. In this case, a narrow sound beam is reflected from the successive layers of tissue surrounding and including the heart, and the relative intensity of the returned signal is plotted as a function of time. One can thus study the relative motions of the heart components.

A more sophisticated variant of this technique is the recording of the returned signal from a triangular section that is swept through by ultrasound. This recorded signal is then played back on a display screen, and the result is a moving picture of the motions, say, of the heart valve. Thus dynamic malfunctions of the valve can be shown in great detail.[6]

Another use of ultrasound in examining the very small is the ultrasonic microscope, one form of which was first developed by Calvin Quate in 1974. Figure 6 shows a scanning acoustic microscope developed by Quate his Stanford colleagues two years ago. A ZnO thin-film transducer is deposited on a sapphire (Al_2O_3) rod. A spherical hollow is made at the front end of the rod; this curved surface acts as a spherical focuser. Acoustic pulses generated by the ZnO transducer pass through the rod and are focused on a spot in the liquid. The object to be examined is placed at or near this focus. The sound reflected from the object then reverses its path and is ultimately converted to an electrical return signal, which is either stored or used to modulate the brightness of an oscilloscope display. The ob-



***Ultrasonogram** of a human fetal scan, side view, middle of third trimester. (Courtesy of S. Blinick, Maine Medical Center, Portland.)* *Figure 5*

ject is scanned in a raster pattern, thus producing an acoustic micrograph (figure 7).

This system improves as the wavelength and the absorption of sound in the coupling liquid decrease. Thus liquid helium, with its very low sound velocity ($\sim$200 m/sec) is a useful coupling liquid. One can achieve further gain by operating at temperatures well below the λ point (about 2K), where the acoustic absorption of the superfluid helium is especially small.

Figure 7 shows a comparison of optical and acoustic images of a silicon-on-sapphire integrated circuit; one can see that the resolutions are comparable. The acoustical system has advantages in depth penetration of the solid, and in distinguishing between superconducting and normal portions of a mixed-state material. The future of this technique looks very bright.

The same might also be said for the related field of electron–acoustic microscopy.[7] A finely focused electron beam is used to probe a sample, and the beam is chopped at rates up to the megahertz range. As the beam energy is absorbed by the sample, there is local periodic heating and hence thermal expansion, the amounts of the latter varying from point to point as a function of the condition of the material. The periodic thermal expansion generates ultrasonic waves which one can then detect and use to form optical images of the substance. A good deal of surface and subsurface information can be gathered with this technique (figure 2).

Absorption

In the propagation of sound, whether in the ocean at audio or near-audio frequencies or in the more restricted zones of the blood system at ultrasonics, the problem of the absorption of sound energy by the medium has long been important. In the early part of this century, experimental measurements of sound absorption in gases were made for the first time. They revealed that the absorption was considerably in excess of what was expected from the classical theories of Stokes and Kirchhoff, who based their studies on shear viscosity and thermal conduction losses, respectively. Fifty years ago, the first reliable experimental measurements were made of sound absorption in liquids, and the discrepancies were even greater.

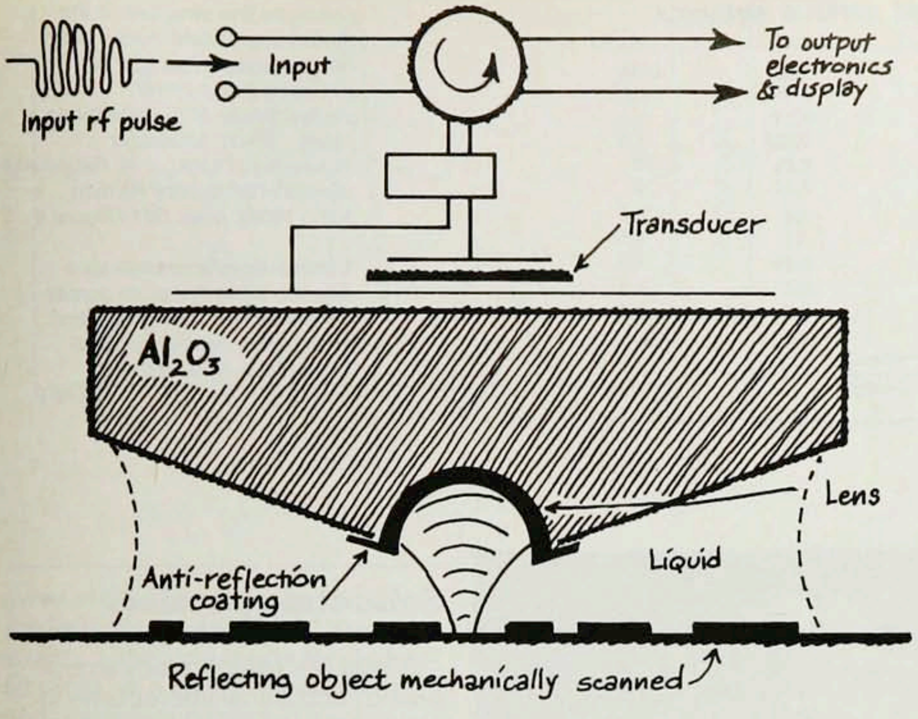
Experimenters had begun to see that classical theory was inadequate, but by then the beginnings of the modern theory were at hand. As suggested by Rayleigh, Jeans and Einstein, the explanation lay in the time delay in the transfer of acoustical energy to the internal degrees of freedom of the system—to rotation and vibration for gas molecules, and to structural or other complicated internal motions of liquids. This delay is referred to as the relaxation time (τ). The sound absorption coefficient per period of the wave, written $\alpha\lambda$, where α is the absorption coefficient per centimeter and λ is the wavelength, can be expressed as

$$\alpha\lambda = \frac{A\omega\tau}{1 + \omega^2\tau^2}$$

where ω is the angular frequency of the sound. Velocity dispersion can be related to the same parameters. Some spectacular successes have been achieved in gases with this theory[8]. With liquids, on the other hand, the situation is a good deal more complex. Relaxation curves have been well documented experimentally, but quantitative theoretical confirmation is often lacking.

Electrolytes

Even more complicated has been the problem of sound absorption in electolytes—a problem that came to the fore in World War II. It was noted that absorption in sea water was about the same as in fresh water when the measurements were carried out in the megahertz range, but at the sonar



Scanning acoustic microscope *developed by Calvin Quate and his colleagues at Stanford. (See* PHYSICS TODAY, *May 1979, page 20.)* *Figure 6*

frequencies then in use (around 100 kilohertz), attenuation was unexpectedly high.

By carrying out measurements in large spheres filled with sea water and exciting the resonance modes of oscillation, Robert Leonard was able to show in the late 1940s that this excess absorption was due to the presence of $MgSO_4$ in the water. This divalent salt had a relaxation frequency of about 140 kHz. Later research by Konrad Tamm and Günther Kurtze in Germany established the relaxation frequencies of a large number of divalent metallic salts. The precise nature of the relaxation was difficult to establish, but some years later, Manfred Eigen, a coworker with Tamm and Kurtze at Göttingen, developed extensively the theory of magnesium sulfate relaxation, involving a multistep dissociation of the salt and attached waters. This work of Eigen opened up a new field of chemical study—the kinetics of fast reactions; for his theoretical contributions to this subject, Eigen was awarded the 1971 Nobel prize in chemistry.

Relaxations in the electrolyte did not end at this point. The relaxation at 140 kHz could be ascribed to the Mg^{++} ion. By going to much high frequencies, Tamm and Kurtze observed that the SO_4 ion relaxed in the region above 300 MHz. More recently, the extensive studies of Fred Fisher and his colleagues, as well as the deep ocean measurements of David Browning, have established even lower relaxation frequencies, some in the neighborhood of 1 kHz. A recent paper by Robert Mellen, Browning and Vernon Simons identifies a large collection of these relaxations, associated with various magnesium and boron salts in the ocean (table I). It would seem that there's nearly always another relaxation to be found if one goes lower or higher in frequency!

Phonons

At about the time of the founding of the American Institute of Physics, a new acoustical concept was taking shape that was to have a profound influence on both acoustics and solid-state physics. This was the idea of the phonon. In 1911 Peter Debye had introduced the idea of interpreting the internal energy of solids as collections of standing acoustic waves of all frequencies, from the lowest mechanical waves of wavelength equal to twice the thickness of the crystal, up to frequencies of the order of 10^{13}/sec. Twenty years later, Igor Tamm spoke of acoustical quanta of energy hf, where f is the acoustical frequency. At about the same time (1932), Jacob Frenkel gave the name "phonon" to such packets.

The phonon is a quasiparticle, and so one can perhaps overidentify its quantized properties; but one of the neatest of its applications is in connection with Brillouin scattering. In such scattering, a light photon enters a liquid. If it absorbs a phonon from the sea of phonons that constitutes the thermal energy of the liquid, it will have an increased energy $h\nu' = h\nu + hf$, where f is the frequency of the absorbed phonon. It also is possible that a phonon may be created at the expense of the original light photon, resulting in a new photon $h\nu'$ of reduced frequency. That is, in general

$$h\nu' = h\nu \pm hf. \qquad (6)$$

Brillouin treated this phenomenon theoretically in 1922, but first-class experimental confirmation had to await the advent of the laser, with its extremely narrow optical line shapes (figure 8). The measurement of the optical frequency shift determines the frequency of the phonon involved, while the widths of the lateral maxima in figure 8 determine the acoustic absorption at that frequency. This Brillouin scattering gave acousticians useful data in the gigahertz range, and a claim to co-ownership rights on the phonon, along with the solid-state physicists.

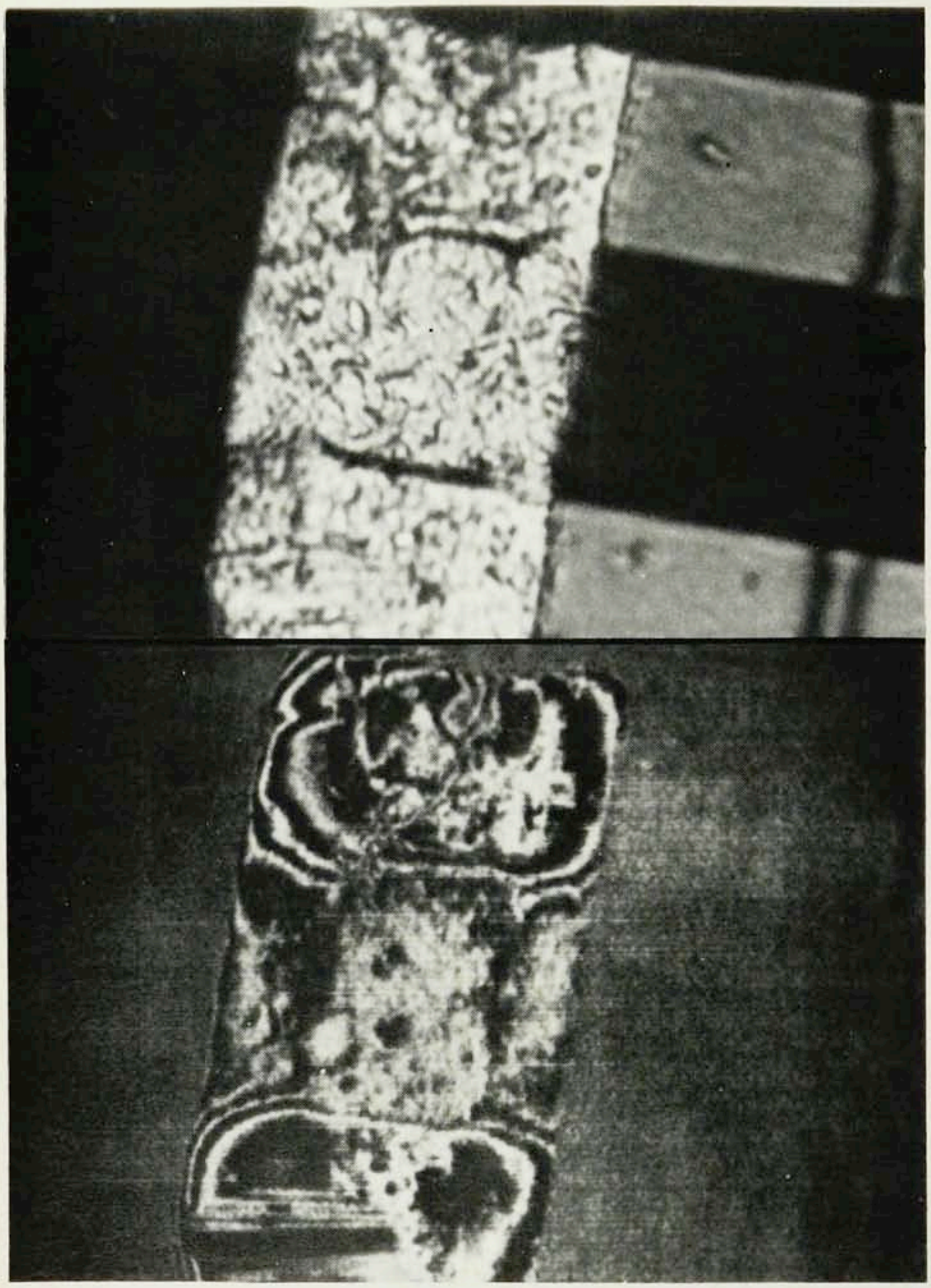
Estimated relaxation parameters of various systems

	f_r kHz	α_{max} dB/km	$(\alpha\lambda)_r$ $\times 10^6$
$B(OH)_3$	0.8	0.01	1.0
$B(OH)_3 + NaHCO_3$	2.2	0.025	1.0
$B(OH)_3 + NaHCO_3 + CaCl_2$	1.0	0.24	20
$B(OH)_3$ (SW)	1.5	0.22	13
$MgCO_3$	25	1.5	5.2
$MgCO_3 + NaCl$	23	1.1	4.1
$MgCO_3$ (SW)	18	0.75	3.5
$Mg\,B(OH)_4^+$	40	0.5	1.0
$Mg\,B(OH)_4^+$ (SW)	30	0.2	0.6
$MgSO_4$ (SW)	125	73	50

All data are for pH = 8.0 at 22°C and for sea-water concentrations

***Brillouin scattering** in benzine produces fine structure in the 6328Å line of light from a Ne–He gas laser. The light is polarized in the plane perpendicular to the scattering plane. (From* Molecular Scattering of Light, *I. M. Fabelinskii, (English translation) Plenum, N.Y. (1968), page 361.) Figure 8*

***Ultrasonic attenuation** as a function of temperature across the superconducting transition in tin, at a frequency of 33.5 MHz. (Data of Morse and Bohm.) Figure 9*



***Scanning-acoustic micrograph** (bottom) of silicon-on-sapphire integrated circuit. Acoustic wavelength is 0.36 microns in superfluid helium. Optical micrograph (top), shown for comparison, has comparable resolution. Polysilicon bars are 10 microns wide. (From J. Heiserman, D. Rugar, C. F. Quate, J. Acoust. Soc. Am. **67**, 1629 (1980). Figure 7*

Solid-state physics

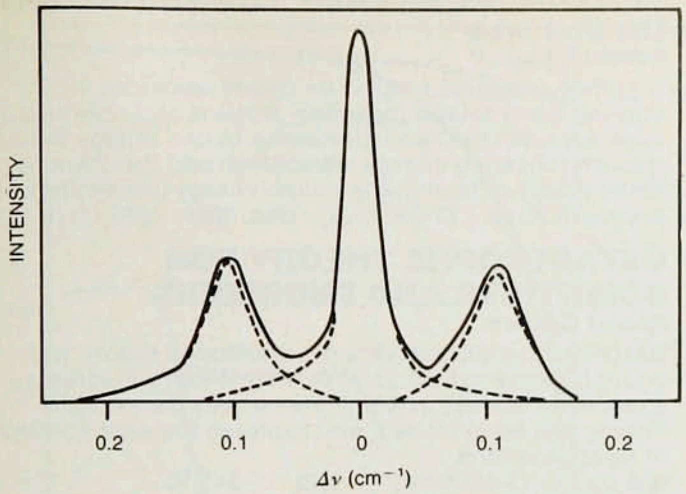
There are far too many examples of acoustical interactions in solid-state physics for me to do justice to them here. I shall therefore take a brief look at only a few of them.[9]

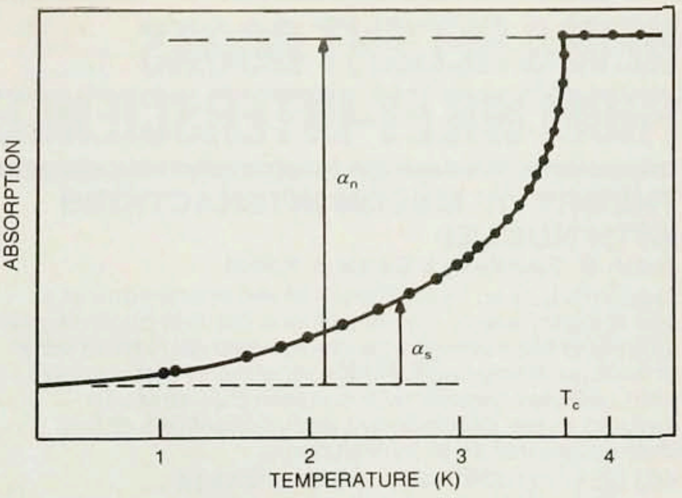
In 1954, Hans Bömmel first observed a sharp decrease in the acoustic absorption of a metal when it became a superconductor. If a magnetic field was then applied to the sample, so as to return it to the normal conducting state, the absorption coefficient rose to a much larger value. Shortly after the appearance of the BCS theory of superconductivity, it was found that the absorption ratio α_s/α_n was closely related to the famous energy gap $\Delta\ (T)$ of that theory:

$$\alpha_s/\alpha_n = 2(1 + e^{\Delta/kT})^{-1} \qquad (7)$$

In fact, the ultrasonic attenuation data of Robert Morse and Henry Bohm (figure 9) were for a time the most reliable source for the determination of Δ. (Figure 9 was shown by Leon Cooper in his Nobel Prize address in 1972).

When an acoustic signal propagating in a solid has a wavelength that is long compared with the mean free path of thermal phonons in the same sample, these phonons see a nearly uniform strain distribution in space. The time variation of this strain continually changes the equilibrium condition of the thermal phonon distribution, and the resultant return to equilibrium is a relaxation process. The attenuation here is known as Akhiezer loss or phonon viscosity. If, on the other hand, the acoustic wavelength is rela-





tively short, the phonons see a spatially rapid variation of the strain. Here one treats the acoustic wave as a beam of phonons and considers phonon–phonon collisions. This energy attenuation is known as Landau–Rumer loss.

In a crystalline solid, dislocations often occur as lines or loops in the lattice, pinned at certain points. The passage of a sound wave through such a crystal is likely to bow out these dislocation lines, and even cause the line to break away from the original pinning points. A successful theory of this sort of attenuation has been developed by Andrew Granato and Kurt Lücke at Brown in 1956. Subsequent studies of this effect have related the acoustic absorption information to nonlinear effects in the crystalline material.

Magnetic interaction

Another important acoustical phenomenon is interaction with magnetic fields, a subject widely studied in the 1960s. One sees acoustic nuclear magnetic resonance where the sound energy is absorbed by exciting components of the spin system to higher magnetic energy levels. Acoustic electron paramagnetic resonance has also been measured. Finally, there are interactions between ultrasound and the spin wave of a ferromagnetic system.

Perhaps the best known of solid-state acoustical interactions is the so-called magnetoacoustic effect in metals, the interaction of the acoustic wave with electrons orbiting in the presence of a magnetic field. This has led to the observation, by Morse and others, of gigantic oscillations of the absorption coefficient as a function of λH, where H is the magnetic field strength. This in turn has provided detailed information about the possible orbits on the Fermi surface and even regarding the shape of the surface itself.

Superfluidity and the five sounds

Finally, we come to the role of sound in a superfluid. Here we find a proliferation of "sounds." We have first, second, third, fourth and fifth sound. The first is, of course, ordinary sound, with oscillations of pressure and density, while the temperature and entropy remain substantially constant. In second sound, it is the temperature and entropy that have the major oscillations, with pressure and density undergoing little change. Here again, acoustics has been related to Nobel prize work, since it was Lev Landau who first developed the theory for determining the velocity of second sound. Landau was awarded the Nobel prize for the totality of his work on superfluidity.

Third sound is a surface wave of the superfluid component in a thin liquid–helium film. Its existence was suggested by Kenneth Atkins in 1958 and was later observed by his group at the University of Pennsylvania.

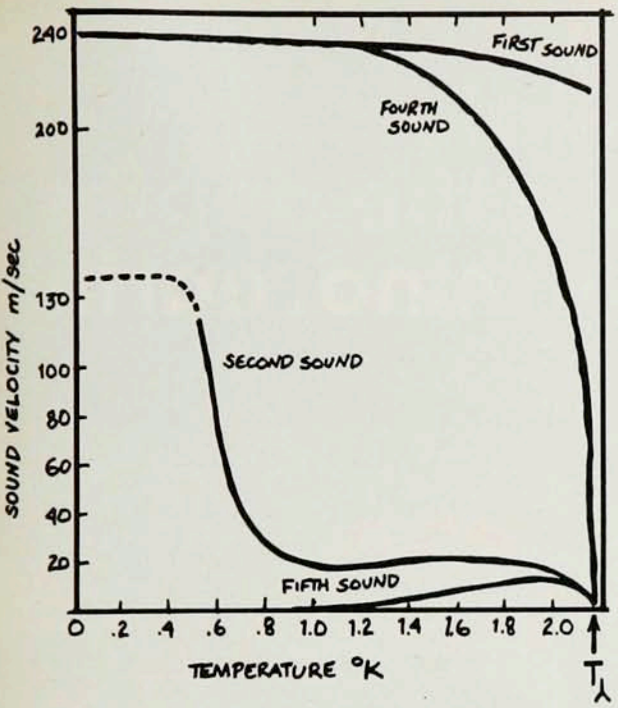
In 1948, John Pellam pointed out the possibility of the existence of fourth sound—pressure waves of the superfluid component in a porous solid (a "superleak") in which the normal component cannot move. Its presence was first observed by Isadore Rudnick and K. A. Shapiro in 1962.

Finally, fifth sound is a thermal wave (akin to second sound) that occurs in the same porous solid. Fifth sound was observed by groups at UCLA and the University of Pennsylvania in 1979. A summary of the properties of these five sounds (thanks to Rudnick) is shown in figure 10.

This discussion of the five sounds pertains only to He^4. However, since He^3 has now also been found to be a superfluid, it may ultimately be possible to discern all these sounds in that liquid as well.

To this collection of sounds we must add still one more—zero sound. The Landau model of a Fermi liquid treats the interactions between the particles as a perturbation, giving a shift of energy levels and transitions of the particles from one level to another. Because of these interactions, the quantum mechanical description must be in terms of "quasiparticles." Such a model is valid only when the quasiparticle lifetimes are sufficiently long that the energy levels are well defined; this occurs only for temperatures below about 0.3 K.

At such temperatures, the Landau model predicts a new mode of sound propagation—zero sound. As the temperature decreases, the time between collisions of quasiparticles becomes longer, increasing (according to the Landau theory) as T^{-2}. At high ultrasonic frequencies, the point is reached for which $\omega\tau \gg 1$, (where τ is the mean thermal phonon lifetime). The resulting zero sound is the analog of sound propagation in rarefied gases where the molecu-



SOUND	NORMAL COMPONENT VELOCITY	SUPERFLUID COMPONENT VELOCITY	TYPE OF WAVE	WAVE VELOCITY
1ST	→	→	PRESSURE DENSITY	$C_1 = \left[\left(\frac{dp}{d\rho}\right)_S\right]^{1/2}$
2ND	→	←	TEMPERATURE ENTROPY	$C_2 = \left[\frac{\rho_s}{\rho_n}\frac{T s^2}{C_p}\right]^{1/2}$
3RD	ZERO	↻	SURFACE WAVE IN FILMS	$C_3 = \left[\frac{\rho_s}{\rho} f d\right]^{1/2}$
4TH	ZERO	→	PRESSURE WAVE IN SUPERLEAK	$C_4 = \left[\frac{\rho_s}{\rho} C_1^2\right]^{1/2}$
5TH	ZERO	→	THERMAL WAVE IN SUPERLEAK	$C_5 = \left[\frac{\rho_n}{\rho} C_2^2\right]^{1/2}$

***Characteristics** of the five sounds. [From I. Rudnick, J. Acoust. Soc. Am. **68**, 36 (1980)]* *Figure 10*

lar mean free path exceeds the wavelength. the existence of zero sound was established in 1963 by B. D. Keen, P. W. Matthews and J. Wilks. Good agreement has now been established between experiment and theory.

An analogous phenomenon occurs in crystalline quartz. It was shown by Humphrey Maris in 1967 that the microscopic theory of sound propagation in crystals at slow frequencies, for which $\omega\tau \ll 1$, yields the ordinary adiabatic velocity of first sound. However, waves of high frequency, for which $\omega\tau \gg 1$, have a velocity that is different from the adiabatic value, and different from the isothermal value that one might have expected. Maris also chose the name zero sound for this phenomenon, and he calculated the difference between the first and zero sound velocities for quartz. In 1970, he and Joseph Blinick produced experimental data in support of this theory.[10]

Six hundred years ago, Geoffrey Chaucer wrote

Soun is noght but air y-broken,
And every speche that is spoken
Loud or privee, foul or fair,
In his substance is but air;
For as flaumbe is but lighted smoke,
Right so soun is air y-broke.

Surely, Geoff, there's much more to it than that!

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