ACOUSTICS

The study of sound, which traditionally crosses departmental boundaries, finds applications in widely separated fields. Apart from the many established areas of music, noise, speech, vibration, and so on, newer applications to physics research are becoming apparent.

LEO L. BERANEK

AN INTELLECTUALLY VITAL and stimulating field, acoustics is rich in unsolved and intriguing research problems. Its areas of interest are pertinent to the activities of many traditional university departments: mathematics, physics, electrical engineering, mechanical engineering, land and naval architecture, behavioral sciences and even biology, medicine and music.

On opening a recent issue of the *Journal of the Acoustical Society of America*, a leading Boston neurosurgeon exclaimed: "It's like Alice's Wonderland. You find a parade of papers on echoencephalograms, diagnostic uses of ultrasound in obstetrics and gynecology, acoustical effects of violin varnish, ultrasonic cleavage of cyclohexanol, vibration analysis by holographic interferometry, detection of ocean acoustic signals, sounds of migrating gray whales and nesting oriental hornets, and sound absorption in concert halls. Certainly no other discipline could possibly be more variegated."

Acoustics assumed its modern aspect as a result of at least seven factors. They are:

- a research program begun in 1914 at the Bell Telephone Laboratories (on the recording, transmission, and reproduction of sound and on hearing) that flourished because of the triode vacuum tube[1]
- the development of quantum mechanics and field theory, which underlay Philip M. Morse's classic text of 1936[2]
- large government funding of research and development during and since World War II, resulting in many valuable acoustics texts[3-22] and, since 1950, a five-fold increase in the number of papers published annually in the *Journal of the Acoustical Society of America*
- a growing public demand in the last decade for quieter air and surface transportation
- the tremendous growth of acoustics study in other countries[23]
- the reconstruction of European dwellings, concert halls and opera houses destroyed during World War II, and the postwar construction of new music centers in the US, UK, Israel and Japan[24,25]
- development of the solid-state digital computer.[26]

Instruction in acoustics has moved steadily across departmental boundaries in the universities, beginning in physics prior to the time of radio and electronics and moving into electrical engineering as the communication and underwater-acoustics fields developed. Then, more recently, it has reached into mechanical engineering and fluid mechanics as the nonlinear aspects of wave propagation and noise generation in gases, liquids and solids have become of prime interest. Also, because much of acoustics involves the human being as a source, receiver and processor of signals that impinge on his ears and body, the subject has attained vital importance to departments of psychology and physiology.

In spite of its variety and its importance to other sciences, acoustics remains a part of physics. It involves all material media; it requires the mathematics of theoretical physics; and, as a tool, it plays a primary role in solving the mysteries of the solid, liquid and gaseous states of matter.

Frederick V. Hunt of Harvard suggests that the field of acoustics might be separated into the categories of sources, receivers, paths, tools and special topics. These are the categories I will use here. Scientists and engineers are active in all these groups, and each group promises exciting frontiers for those entering the field.

SOURCES OF SOUND

The sources that we must consider include speech, music, signals, and a variety of generators of noise.

Speech

One of the most challenging goals of

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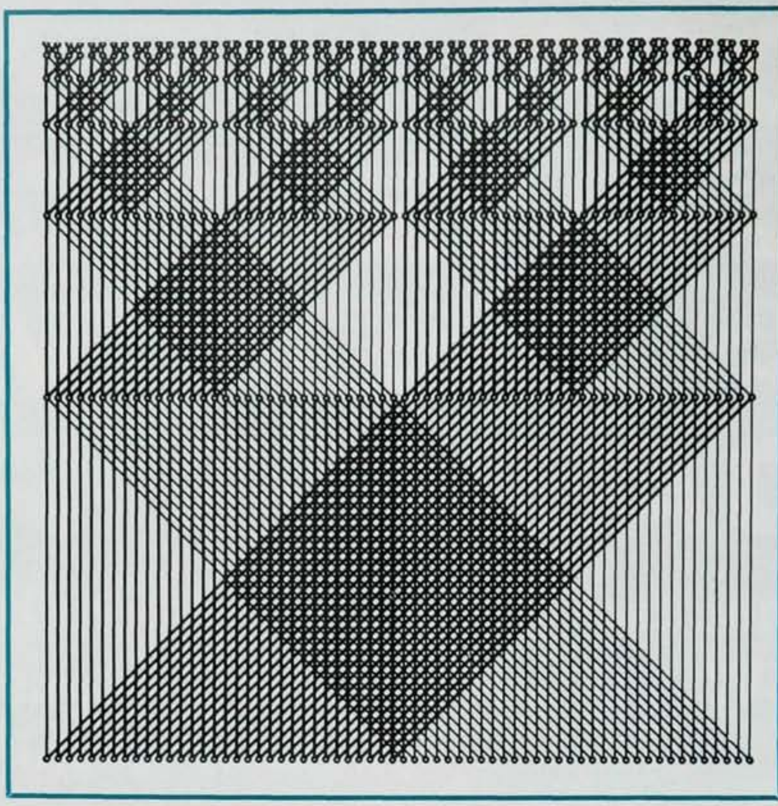


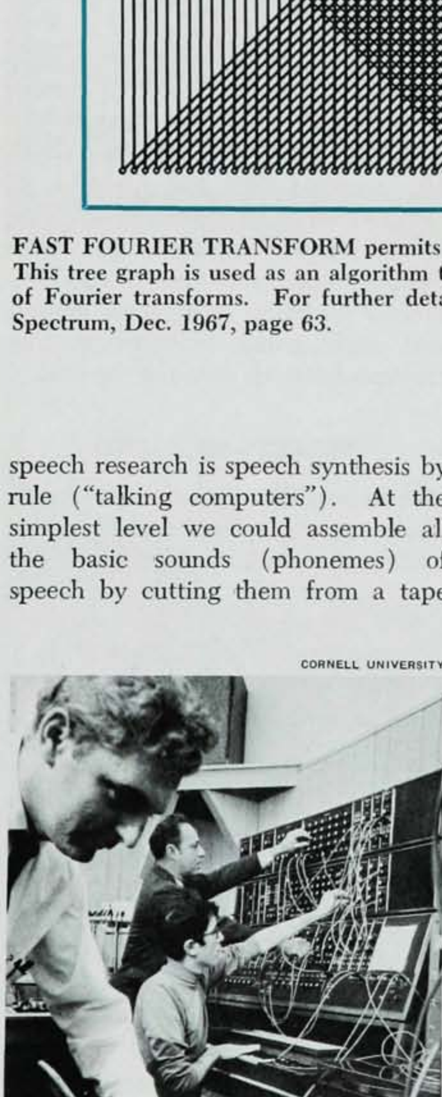
FAST FOURIER TRANSFORM permits a spectral analysis of sounds in near-real time. This tree graph is used as an algorithm to obtain factored matrices in the computation of Fourier transforms. For further details see E. O. Brigham, R. E. Morrow, IEEE Spectrum, Dec. 1967, page 63. —FIG. 1

speech research is speech synthesis by rule ("talking computers"). At the simplest level we could assemble all the basic sounds (phonemes) of speech by cutting them from a tape recording and calling them up for reproduction, thus producing connected speech according to a set of instructions. But this procedure works very poorly, because perceptually discrete phonemes, when combined by a person talking to produce syllables, have a modifying influence on each other. Thus stringing together phonemes to produce good speech would require a very large inventory of recorded units.

Workers at the Haskins Laboratories and at Bell Labs agree on these fundamentals, but have taken somewhat different approaches. Bell Labs uses the digital computer to assemble natural utterances by appropriate modification of pitch, stress and duration of words spoken in isolation. One of the Bell Labs methods applies the principles of predictive coding. However, the basic problem remains: How does one structure the computer "brain" so that it will select, modify and present a sequence of sounds that can carry the desired meaning in easily interpretable form?

The geographers of speech have received new impetus with relatively recent, easy access to large computer power. A potent tool for this work is the fast Fourier transform, which allows spectral analyses of sounds with high resolution in near-real time (figure 1). Accompanying this process are new methods for three-dimensional display of speech spectra with continuously adjustable resolution in time and frequency. Thus deeper insights into the structure of speech signals and their spectra are slowly becoming possible. The problem is to select the meaningful parameters of the primary information-bearing parts of speech and to learn how they are superimposed on, or modulate, the secondary parameters that are associated with accent and individual style and voice quality.

CORNELL UNIVERSITY



ELECTRONIC MUSIC. Robert A. Moog is here seen (left) at the keyboard of one of his "synthesizers" that generate and modify musical sounds. —FIG. 2

Music

Currently, the availability of rich avant-garde sounds is stirring creative activity in acoustics and music. Solid-state devices are generally responsible for this incipient revolution, partly because they permit complex machines in small space (figure 2), but also because of their lower price.

The initial period of bizarre, experimental, musical sounds is passing; music critics speak more frequently of beauty and intellectual challenge. Soon a new version of musical form and sound will evolve and, as decreasing costs widen the availability of new instruments, recreational composing may eventually occupy the leisure time of many individuals. Hopefully these new sounds and compositions will excite educated people to an extent not observed since the 18th century.

The on-line computer will also play its part, permitting traditional composers to perfect their compositions with an entire orchestra at their fingertips.[26]

Composers in all eras have had some specific hall-reverberation characteristics in mind for each of their works. Some modern composers now can see the exciting possibility of the expansion of artificial reverberation to permit reverberation times that change for different parts of a composition, and are different at low, medium and high frequencies.

Perhaps the greatest progress will be made by those trained from youth in both the musical arts and physics, so that the novel ideas of the two disciplines can be combined to produce results inconceivable to the classical composer. Early stages of this type of education are under way in

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CLOWES MEMORIAL HALL, Butler University, Indianapolis. The acoustics of this hall (Johansen and Woollen, architects, and Bolt Beranek and Newman Inc, consultants) are acknowledged to be among the best of contemporary halls. Research is needed to explain why this hall is superior, to the ears of musicians and music critics, to Philharmonic Hall in New York. The same general principles were used in the design of the two halls, which opened at about the same time. —FIG. 3

universities in the Boston, New York and San Francisco areas.

Noise

Noise sources must be understood if they are to be controlled, but the study of them has often been neglected in the past. Many challenges appear in the understanding and control of high-level, nonlinear vibrations, including nonlinear distortion, harmonic and subharmonic generation, radiation forces and acoustic wind.

Aerodynamic noise looms large on the research frontier. For example, the periodic aerodynamic loads associated with noise from helicopter blades are not well understood, particularly as the stall point of the blades is approached. Multiple-rotor helicopters, in which one set of blades cuts through the vortices produced by the other set, offer important possibilities for theoretical investigation. For example the helicopter rotor must operate in unsteady air flow, but this condition produces uneven loadings, random stresses on the blades and magnified vortex production. The fuselage of the helicopter also affects the noise produced.

Surprisingly, noise production by jet-engine exhausts is not yet well understood, although large sums of money have been spent on "cut-and-try" muffling.

Perhaps least understood of all mechanical sources of noise is the impact of one body on another. For example even the sound of a handclap has never been studied. The noise of engine blocks and industrial machinery is largely produced by impacts. The production of noise by hammers, punches, cutters, weaving shuttles, typewriter keys and wheels rolling on irregular surfaces is also largely unexplored.

RECEIVERS OF SOUND

The most important receivers of sound are people—those who use sound to aid them, as in listening and communication, and those who are bothered by the annoying or harmful aspects of noise. Much engineering effort is constantly expended to better the acoustic environment of people at home and at work. In some areas the basic understanding of noise problems is well developed, and engineering solutions are widely available. In others, such understanding is only beginning to emerge and engineering solutions are still uncertain.

Variety and complexity

The intellectually interesting questions related to human beings as receivers of sound derive in large part from the extraordinary variety in the physical stimuli and the complexity of human responses to them. The questions include: What are the few most important physical descriptions (dimensions) that will capture the essence of each complex psychophysical situation? How can the variety of stimuli be catalogued in a manageable way so that they can be related to the human responses of interest?

Many of the sources of sound are so complex (a symphony orchestra, for example) that simplified methods must be used to describe them and to arrive at the responses of things or people to them. The dangers in simplified approaches, such as statistical methods for handling room or structural responses, are that one may make wrong assumptions in arriving at the physical stimulus-response description, and that the description may not be related closely enough to the psychophysical responses. The process of threading one's way through these dangers is a large part of being on the research frontier. Good examples of the perils are found in architectural acoustics (figure 3).

Concert halls

In 1900, Wallace C. Sabine gave room acoustics its classical equation.[27,28] Sabine's statistically based equation for predicting reverberation time (that is, the time it takes for sound to decay 60 decibels) contains a single term directly proportional to the volume of a room and inversely proportional to the total absorbing power of the surfaces and contents. A controversy exists today as to its relevance to many types of enclosure. Research at Bell Labs, aided by ray-tracing studies on a digital computer,[26] shows that the influence of room shape is of major importance in determining reverberation time, a fact not recognized in the Sabine equation. A two- or three-term equation appears to be indicated, but until it is available there are many subtleties that confront the engineer in the application of published sound-absorption data on acoustical materials and objects.[29,30]

Reverberation time is only one of

the factors contributing to acoustical quality in concert halls. A hall with *either* a short or a long reverberation time, may sound either dead or live.[26] Of greater importance, probably, is the detailed "signature" of the hall reverberation that is impressed on the music during the first 200 milliseconds after the direct sound from the orchestra is heard.[25]

It would be easy to simulate the reverberation signature of a hall by earphones or a loudspeaker, were it not that spatial factors are of primary importance to the listener's perception. Reflections that come from overhead surfaces are perceived differently from those that come from surfaces in front, and from surfaces to the right, left and behind the listener. A new approach suggests that with a number of loudspeakers, separated in space about a listener and excited by signals in precise relative phases, one can produce the direct analog of listening in an auditorium.

Frequency is a further dimension. To be optimum, both the 60-dB reverberation time and the 200-msec signature of the hall should probably be different at low, middle and high frequencies.

There are many other subjective attributes to musical-acoustical quality besides liveness (reverberation time). They include richness of bass, loudness, clarity, brilliance, diffusion, orchestral balance, tonal blend, echo, background noise, distortion and other related binaural-spatial effects.[25] Computer simulations may lead to the separation of a number of the variables involved, but analog experiments conducted in model and full-scale halls will most likely also be necessary to improve our understanding of the relative importance of the many factors. These studies would be very costly and would need Federal support. The prospect of greater certainty in design of concert halls makes this an exciting frontier for research.

Psychoacoustics

Traditional advances in psychoacoustics have resulted from investigation of the basic aspects of hearing: thresholds of audibility (both temporary and permanent), masking loudness, binaural localization, speech intelligibility, detectability of signals in noise, and the like.[6] Just as in the case of structures, humans exhibit a multiplicity of responses to different noise situations. Those on the forefront of research are attempting to find simplified statistical descriptions of the various physical stimuli that correlate well with several subjective responses, such as annoyance.

As an example, a recent means for rating the subjective nuisance value of noises[31] says that the nuisance value is greater as the average level of the noise is increased and is greater the less steady it is. In other words, the nuisance is related to the standard deviation of the instantaneous levels from the average; the background noise, if appreciable, is part of the average level. But there is no treatment of the "meaning" in the noise (the drip of a faucet would not be rated high, although it might be very annoying), or of special characteristics —such as a shrill or warbling tone, or a raucous character. Although this formulation is probably an improvement over previous attempts to relate annoyance to the level of certain types of noise, the whole subject of a person's reaction to unwanted sounds is still wide open for research.

Another forefront area of psychoacoustics is the response of the tactile senses to physical stimuli, both when the body is shaken without sound and when the body and the hearing sense are stimulated together. We know that discomfort in transportation is a function of both noise and body vibration. How the senses interact, and whether or how they mask each other, is not known. Neither do we understand the mechanism by which the hearing process takes place in humans beyond the point where the mechanical motions of the inner ear are translated into nerve impulses. We also do not know whether extended exposure to loud noise or to sonic booms has detrimental physiological or psychological effects, other than damage to the middle ear. We have not adequately analyzed the nonlinear behavior of the ear and its effect on enjoyment of music or understanding of speech.

UNDERWATER AND AIRBORNE PATHS

Several major problem areas exist in underwater and airborne sound propagation. One is prediction of acoustic propagation between two points in the ocean over distances up to several hundred times the depth of the water. Involved are many alternate paths of propagation, spatial distributions of pressure and temperature, spatial and temporal fluctuation resulting from waves, suspended particles, bubbles, deep-water currents and so on. Mathematical physics and the computer have proven that strictly deterministic thinking about sound propagation is frequently fruitless. The need is to characterize *statistically* the transmission between two points in both amplitude and phase. The ultimate value of this research is to distinguish information-bearing signals from all other sounds in which they are immersed.[32] Similar needs exist in air. In short, this area is an important element of the acoustical frontier.

Structural paths

When sound or vibration excites a structure, waves are propagated throughout it and sound is radiated to the surrounding medium. An understanding of the physics of these phenomena, adequate to quantitative prediction of the effect of changes in the structural design on them, is required for many applications. The response of buildings to sonic booms, including the noise generated by objects in the building set in vibration by the boom, is one example.[33] Many other examples arise in connection with buildings and transportation vehicles, including underground, ground, marine, air and space vehicles.

Structures and the noise and vibration fields in them are generally complex beyond description. Almost invariably, the vibrational properties of an existing structure cannot be determined in a way consistent with setting up the dynamical equations of motion and arriving at solutions to them on a computer. Furthermore, the real interest is in *predicting* response for a structure that has not been built. Again the problem is, in principle, *deterministic* (solvable on a computer) but one does not ever know the parameters to use. Progress is now resulting from the invention of a new language, a statistical mathematical approach, for describing what goes on.[34] But the dangers, as in room acoustics, are that the answer may be incomplete. It is necessary to go back repeatedly to the laboratory experiment and try to improve the language, the vocabulary of statistical assumptions, that is used to describe the physical situation. The added dimension of damping, nonhomogeneity of structures, and radiation into media of widely different properties (air and water) make this field rich in research topics.[20,35]

ACOUSTIC TOOLS

Satisfaction of the needs of tool seekers is a lush field for the acoustical inventor. Here is where the acoustic delay line is perfected for radar systems and process-control computers; where sound is used to help clean metals and fabrics; where vibration is used to process paints, candy, and soups; and where ultrasonics is used to test materials nondestructively. Transducers of all types, seismic, underwater, vibration, microphones, loudspeakers, and so forth are constantly being improved. The medical profession seeks help from ultrasonics as a means of detecting objects or growths imbedded in the body, or as a means for producing warming of body tissue. The whole field of spectrographic analysis of body sounds as an aid to medical diagnosis is largely unexplored. Special tools such as sonic anemometers and sonic temperature- and velocity-sensing devices, are just becoming available.

SPECIAL TOOLS

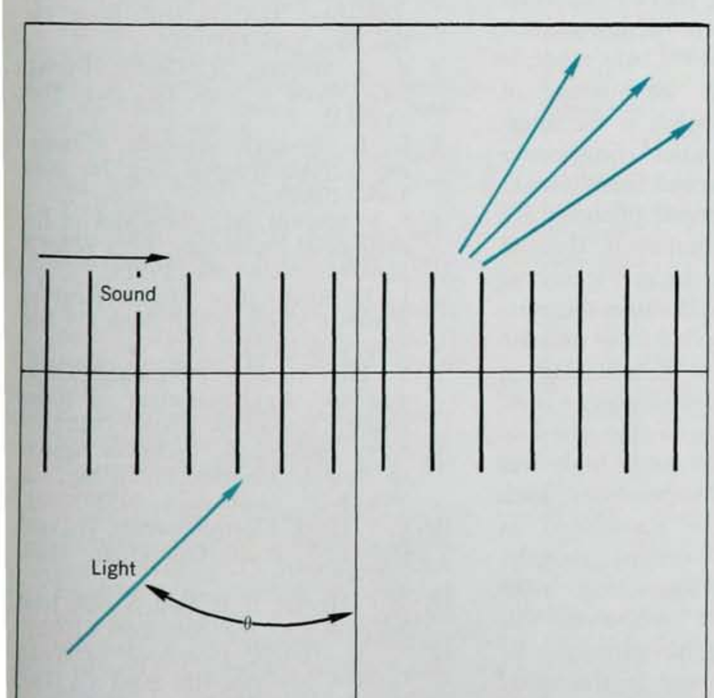
The *Physical Review Letters* attest to a renaissance of acoustics in physics during the past decade. High-frequency sound waves are being used in gases, liquids and solids as tools for analyzing the molecular, defect, domain-wall and other types of motions in these media. High-frequency sound waves interact in various media with electric fields and light waves at frequencies for which their wavelengths in the media become about alike (typically 10^8 to 10^{12} Hz). From these basic investigations, practical devices are emerging for signal processing, storage and amplification, for testing, measurement, inspection, medical diagnosis, surgery and therapy, and for ultrasonic cleaning, welding, soldering and homogenizing.[3,18]

Plasma acoustics

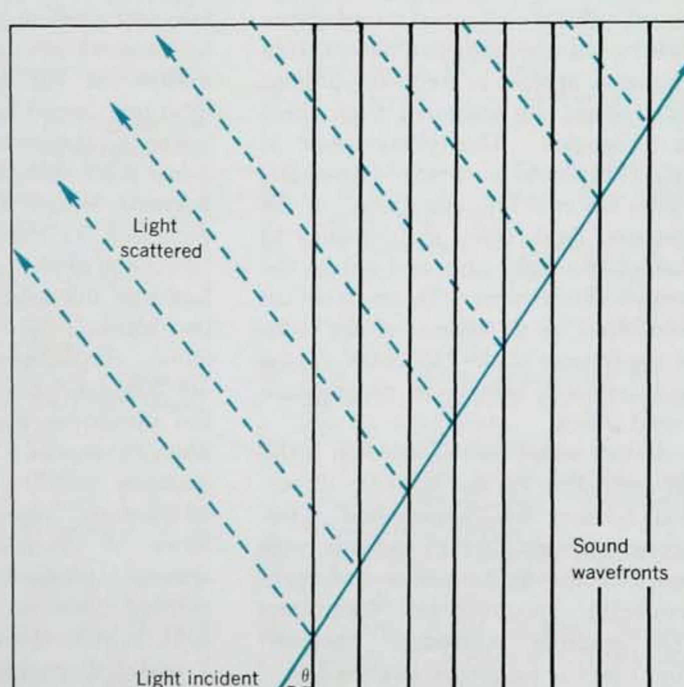
Plasma acoustics is concerned with the dynamics of a weakly ionized gas.[3] The electrons in the gas (with a temperature of 10^4 to 10^5 K, typically) will draw energy from the electric field that maintains the plasma. Because of the lower temperature of the neutral gas (500 K, typically), much of this energy is transferred to the neutral-gas particles through elastic collisions. If this transfer is made to vary with time, for example, by a varying external electric field, a sound wave is generated in the neutral gas. Alternatively, the electric field may be held constant and the electron density varied by an externally applied sound wave. When the frequency and other parameters are in proper relation, a coupling of the electron energy to the acoustic wave may create a positive feedback that results in sound amplification.

Current research involves examination of the acoustic instabilities that result from this amplification and in the determination of the conditions for spontaneous excitation of normal modes of vibration, such as in a tube. Because there is coupling between the neutral gas and the electrons, the sound-pressure field can be determined in terms of the electron-density field. Thus an ordinary Langmuir probe, arranged to measure fluctuations in the electron density, can be used as a microphone in the weakly ionized gas. This technique has proved useful in the determination of the speed of sound and the temperature, of the neutral-gas component in a plasma. It also appears to be a promising tool in the study of density fluctuations in jet and supersonic wind-tunnel flow.

In a fully ionized gas there exists a type of sound wave, called "plasma oscillation," in which there is charge separation. The speed of propagation of this ion-acoustic longitudinal wave is determined by the inertia of the ions and the "elasticity" of the electrons. In the presence of a magnetic field, the plasma becomes nonisotropic; the wave motion then becomes consid-



DEBYE-SEARS SCATTERING. A beam of light, passed through a fluid at an angle to the direction of a sound wave, diminishes in amplitude, and first-order diffracted waves appear. —FIG. 4



BRILLOUIN SCATTERING by a sound wave wide compared with the wavelength of the light, generates two new frequencies —that of the light plus and minus the acoustic frequency.—FIG. 5

erably more complicated, creating an interesting area for research.

Optical acoustics

The density fluctuations caused by a sound wave in a gas, liquid or solid, produce corresponding fluctuations in the index of refraction, and this leads to scattering and refraction of light. Conversely, under certain conditions, sound can be generated by light.[3]

To illustrate Debye–Sears scattering (figure 4), a beam of light is passed through a fluid at an angle with respect to the direction of travel of a narrow-beam sound wave. The sound wave acts somewhat like an optical transmission grating, except for its finite width and time and motion dependence. If the light penetrates at a right angle to the direction of propagation of the sound wave, the incident light beam diminishes in amplitude, and first-order diffracted waves appear at angles $\pm\theta$, where $\sin\theta$ equals the ratio of the wavelength of the light to that of the sound.

When the width of the sound wave is very large compared to the wavelength of light, the wavefronts of the sound in the medium form a succession of infinite partially-reflecting planes traveling at the speed of sound, and the scattered light occurs in only one direction. At very high frequencies (10^9 to 10^{10} Hz) the primary scattered wave is backward, and the effects of thermal motion of the medium on scattering are easily observed. Because thermal sound waves travel in all directions and have a wide frequency spectrum, frequency-shifted light beams are scattered from them at all angles. This phenomenon is called "Brillouin scattering" (figure 5). There are two Brillouin "lines" in the scattered light, equal in frequency to that of the light plus and minus the acoustic frequency. These lines are broadened by an amount of the order of the inverse of the "lifetimes" of the ordinary and transverse propagating sound waves.

A very active area of research is the determination of the acoustic dispersion relation for "hypersound" (frequencies above 10^9 Hz) in fluids, with lasers as the light sources and high-resolution spectroscopic techniques (for example heterodyne spectroscopy) for the frequency analysis.[3]

Other frontiers

Other areas of research are reported in *Physical Review Letters,* as already mentioned, and in the *Journal of the Acoustical Society of America* and elsewhere.

One such frontier involves the collective modes of vibration in liquid helium. In particular, the sound attenuation has been measured at temperatures very close to absolute zero with incredible accuracy, with and without porous materials present in the liquid.[36]

An interesting geophysical problem is the generation of seismic waves by sonic booms[37] from supersonic aircraft at high altitudes. When the seismic waves travel at the same speed as the phase velocity of the air wave, efficient and effective coupling of energy from the acoustic mode to the seismic mode takes place. One application of this coupling effect is as a tool to determine surficial earth structure.

Holographic imaging has attracted interest because it offers the possibility, first, of three-dimensional image presentation of objects in opaque gases or liquids, and, second, of recording and utilizing more of the information contained in coherent sound-field configurations than do the more conventional amplitude-detecting systems.[38] Holographic imaging has been done in an elementary way at both sonic and ultrasonic frequencies and in air and water. Figure 6 shows an example.

Much recent research in physical acoustics is concerned with ultrasonic absorption in solids, particularly crystals, explained in terms of attenuation by thermal photons.[18] An intrinsic mechanism for the attenuation of ultrasonic sound in solids is the interaction of the mechanical (coherent) sound wave with thermal (incoherent) phonons, where thermal phonons are described as the quantized thermal vibrations of the atoms in the crystal lattice of the solid. Because the relation between the applied force and the atomic displacements is nonlinear, a net "one-way" transfer of energy from the ultrasonic wave to the thermal phonons results. At very high frequencies and low temperatures, such interactions must be considered in terms of discrete events, namely, acoustic phonons interacting with thermal phonons.[18,39] Also in this field, light scattering has proven to be a useful diagnostic tool in the study of sound and crystal properties.[40]

Just as we may have interaction between sound waves and electrons in a gaseous plasma, sound and electrons may interact in certain semiconductors. In a semiconductor the tension and compressions of the acoustic wave create an electric field that moves along with the traveling wave. If an intense steady electric field is applied to the semiconductor, the free electrons will try to go somewhat faster than the sound wave, and the sound wave will increase in amplitude, provided the thermal losses in the crystal are not too great. This interaction requires extremely pure crystalline material.[41]

Attempts are underway to make ultrasonic delay lines adjustable, by drawing upon the interaction between acoustic waves and magnetic "spin waves." Fermi-surface studies for many metals can also be carried out by measuring attenuation in the presence of magnetic fields.

One application for surface (Rayleigh) waves on a crystalline solid is in signal processing. Surface waves are accessible along their entire wavelength and are compatible with integrated-circuit technology. Perhaps

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such waves at GHz frequencies can be used to build mixers, filters, couplers, amplifiers, frequency shifters, time compressors and expanders, and memory elements.[42]

In the study of high-frequency surface waves, laser light again proves to be a useful diagnostic tool. With it, the thermally excited surface waves in liquids have been studied by techniques quite similar to the Brillouin scattering from phonons.[43] One application is determination of surface tension through observation of the mean frequency and bandwidth of such waves.

Many more examples of modern physical acoustics could be cited, but these examples should prove my opening statement that acoustics is a vital, growing field.

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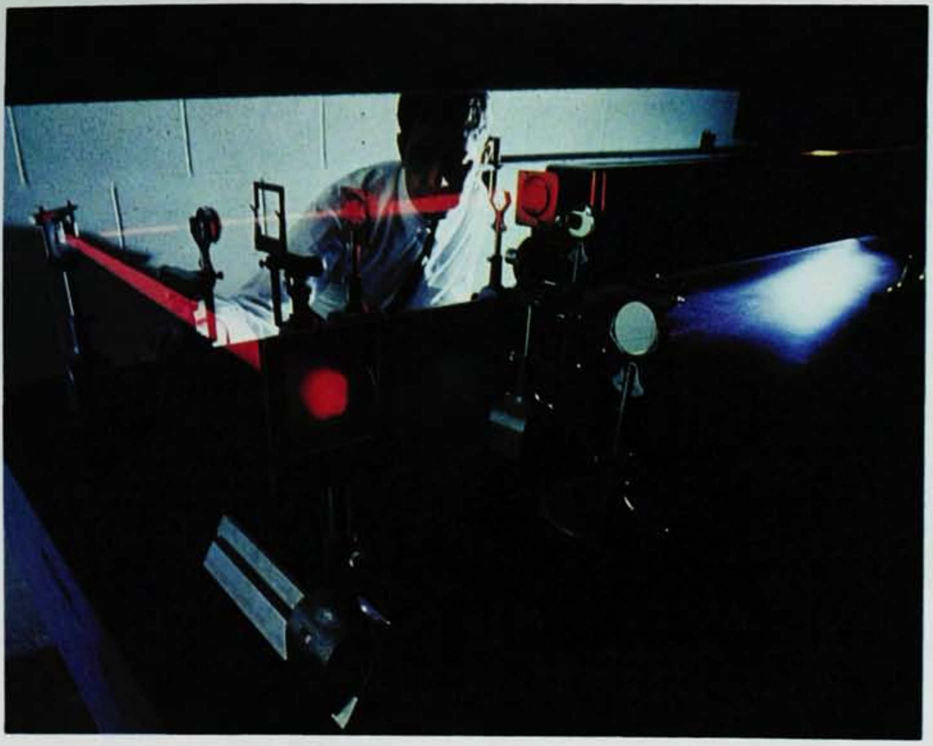

ACOUSTICAL HOLOGRAPHY. Acoustical wavefronts reflected from irregular surfaces can be recorded and reconstructed with coherent laser light. An advantage over conventional holography is that optically opaque gases and liquids can be penetrated. The experiment shown is in progress at the McDonnell Douglas Corp. —FIG. 6

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