ULTRASON

Some three thousand years ago, according to the Old Testament, Joshua, the son of Nun, led the Israelites over the river Jordan into the promised land. And then, once each day for six days, seven priests carrying seven trumpets made of rams' horns circled the walled city of Jericho. And on the seventh day the priests circled the walls seven times, and on the seventh time the priests blew a loud blast on the trumpets, and the Israelites shouted a loud shout, and the walls of Jericho fell down flat. Thus must history reach back into antiquity to find the first allusion to the use of sound energy for a purpose other than hearing.

Thirty centuries later, in the field of ultrasonics, spectacular use is again being made of "sound" energy. Although inaudible to the human ear, ultrasonic "sound" waves have all the physical properties of audible sound waves, differing only in frequency. But it is this difference in frequency, and the consequent concentration of energy, which leads to the very different effects obtainable with ultrasonic waves.

Audible sounds, or sonic waves, range in frequency from about twenty cycles per second to about twenty kilocycles per second. Ultrasonic waves are defined as vibrational or "sound" waves which have a frequency higher than twenty kilocycles. Whether or not inaudible vibrational waves should be called sound waves is a debatable issue, depending for its resolution on the definition of sound on a physical or on a psychological basis. Not many years ago the waves now known as ultrasonic went under the name of supersonic. This latter name left a lasting impression in the field of radio. Although radio waves are electromagnetic rather than sound waves, the intermediate frequency used in the most popular type of radio receiver was in the "supersonic" frequency range, and led to the designation of this receiver as a supersonic heterodyne, or, more briefly, a superheterodyne receiver. When the aviation industry appropriated the word supersonic to refer to *velocities* greater than that of sound, physicists were forced to devise the word ultrasonic for *frequencies* higher than those of audible sound. To retain its original meaning the superheterodyne receiver should today be called ultraheterodyne!

Properties

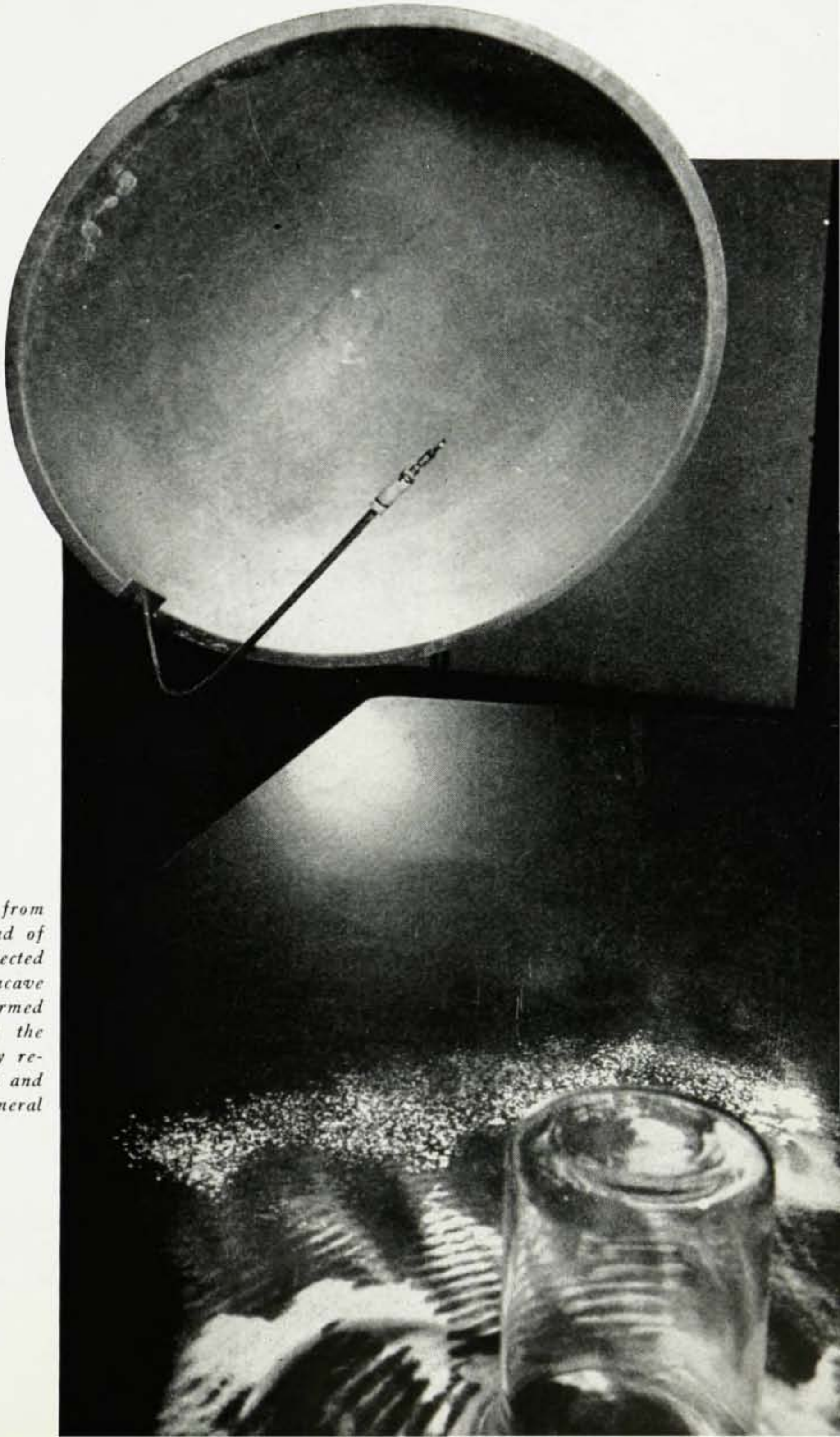
The properties which give rise to the unusual effects of ultrasonic waves follow from principles which are common to all wave phenomena. In a given medium the wavelength of a wave is inversely proportional to the frequency, so a high frequency implies a short wavelength. Furthermore, the directional character of wave propagation is a function of the wavelength. Suppose that a vibrating circular piston is used to generate sound waves. If the frequency is low the waves spread out from the source in all directions and bend around corners. As the frequency is raised the waves begin to assume directional characteristics, that is, more of the wave energy is propagated in certain directions than in others and bending becomes less pronounced. At high frequencies most of the wave energy is concentrated in a truncated cone. The angle of the cone is a function of the ratio of the wavelength of the wave to the diameter of the piston source; the smaller the ratio, the smaller the angle of the cone. Waves of high frequency, or short wavelength, will therefore be propagated essentially in a given direction with negligible bending. Ultrasonic waves have been generated at frequencies as high as five hundred megacycles, corresponding to a wavelength in air equal to

Arthur R. Laufer, assistant professor of physics at the University of Missouri, has come only recently to work with ultrasonics. It was his recent reading of an article on the subject by R. W. Wood in the Philosophical Magazine (1927) which stimulated his interest. A search of the journals showed that a great deal of research needed to be done in the field and that it had wide potentialities. Laufer's previous work was with Geiger counters, and he taught at Yale, Michigan State, and NYU before coming to Missouri.

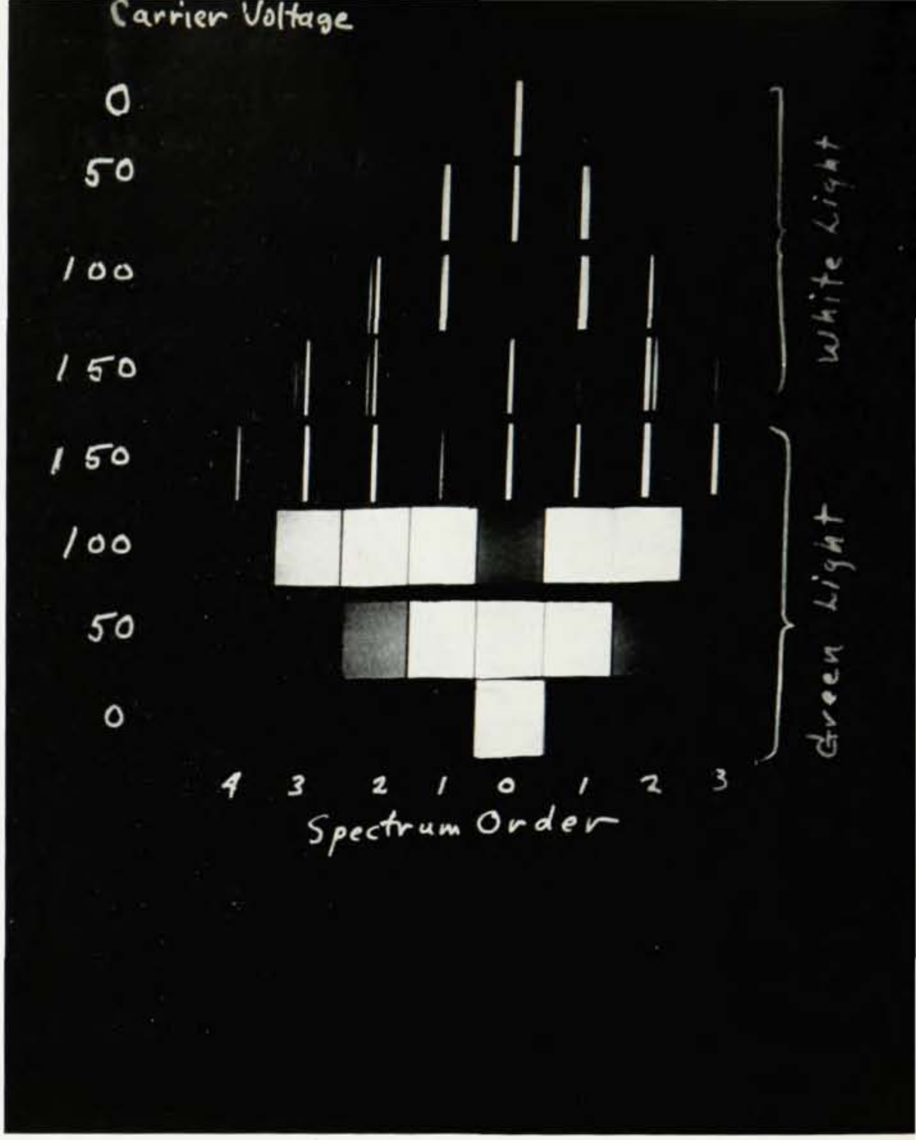
ICS

Within the last few years there has opened up in acoustics a field for pioneers in fundamental and applied research which is growing in vigor. Its promise is here surveyed.

by Arthur R. Laufer



Ultrasonic waves, coming from the tiny whistle on the end of the J-shaped tube, are reflected on to the table by the concave metal disk. The ridges, formed in talcum powder, show the standing waves formed by reflections from the table top and beaker. Photo courtesy General Electric Company.



The Debye-Sears light diffraction effect. Parallel light is beamed at right angles through a cell containing a liquid in which standing ultrasonic waves have been formed by a vibrating crystal. The alternate regions of compression and expansion form a kind of diffraction grating, but the extent to which light is passed to each of the various orders depends on the amplitude of the standing waves and hence on the voltage applied to the crystal. This photograph shows the diffraction spectra produced by ten megacycle waves in water. The upper narrow line spectra are obtained by using a narrow slit aperture for the light which crosses the cell. The lower broad spectra are made with a very wide slit which is used in light valving. Note that at 100 volts little or no light is left in the center (or zero) order.

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that of visible red light. Such ultrasonic radiation has all the directional properties of a beam of light. Unfortunately, the attenuation of the radiation is also proportional to the frequency, or rather to the square of the frequency, so that sharply defined beams cannot be propagated over long distances. Nevertheless, even at frequencies as low as twenty kilocycles, beams of ultrasonic waves are well enough defined to be used in submarine detection.

The *intensity* of radiation being defined as the energy passing through a unit area per unit time, it is apparent that the concentration of ultrasonic radiation into a cone makes it possible to produce beams of very high intensity. During the past decade ultrasonic sources have been made to generate as much as fifty watts per square centimeter, and beams of radiation have been focused to yield intensities as high as five thousand watts per square centimeter. These magnitudes become impressive when compared with the intensities of familiar audible sounds. At a distance of two meters from a trumpeter the sound intensity is about one millionth of a watt per square centimeter. If all the sound energy generated by a full symphony orchestra could be concentrated in a point source, at a distance of two meters the intensity would be about one ten-thousandth of a watt per square centimeter which is the threshold of pain for the human ear. If all the residents of New York City (population about seven million) were to speak at the same time, the total power they would generate would be just about enough to light a sixty watt lamp. Obviously, the intensities attainable with ultrasonic waves are enormous in comparison with those in the audible range. The phenomena discovered in the field of ultrasonics are the direct result of the short wavelength and the concomitant high intensity of ultrasonic waves.

Early Generators

The first man-made generator of sustained ultrasonic waves was designed as long ago as 1883, when a forced-air whistle reached the frequency of twenty-five kilocycles. Nature, however, anticipated the work of man by endowing the bat with an ultrasonic generator of its own. Using the vocal cords in its larynx, the bat generates and emits sound waves in pulses of two milliseconds duration at a rate of about thirty per second. The frequency in each pulse ranges from about thirty to one hundred kilocycles. Reflections received by the bat's ears indicate the location of obstacles, and, in this radar-like manner, ultrasonic radiation is used by the bat to guide itself in flight.

Following the forced-air whistle, a tuning fork with tines only several millimeters in length was developed near the end of the last century, with a frequency ranging as high as ninety kilocycles. Both the whistle and the fork, however, yielded frequencies which could not be controlled accurately and output powers which were relatively small. There was but little further progress in the development of ultrasonic generators until the first World War when Professor Paul Langevin, director of the School of Physics and Chemistry in Paris, was requested by the French government to devise some method of detecting submarines to combat the U-boat menace.

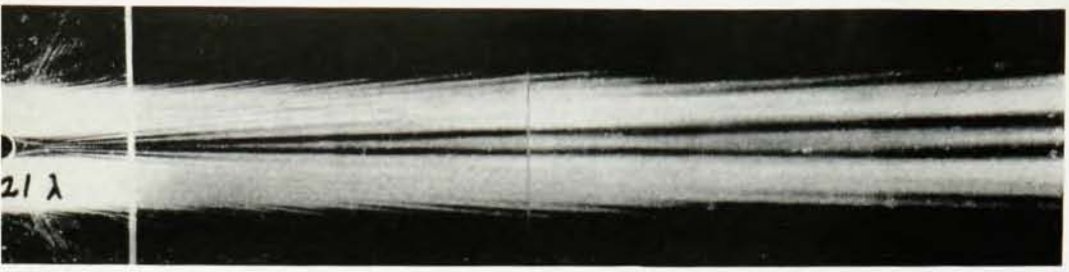
A few years earlier, following the *Titanic* disaster, an Englishman named L. F. Richardson suggested that a hydraulic whistle be used to locate underwater navigational hazards such as icebergs through the echo of a narrow beam of ultrasonic waves, but experiment proved his apparatus to be ineffective. Then, in 1915, a Russian engineer named Chilowski proposed that ultrasonic vibrations be excited in a mica condenser by a Poulsen arc, and that the radiation from the vibrating condenser be used for underwater detection. Professor Langevin tested and then developed Chilowski's idea to such an extent that a transmission range of two thousand yards in the Seine River was attained early in 1916, despite the fact that the frequency stability and power output of the generator still left much to be desired. Shortly thereafter, two unrelated scientific discoveries were combined by Langevin to provide for the first time a dependable source of ultrasonic waves of controllable frequency and intensity. To replace the inherently unstable Poulsen arc, Langevin chose the newly developed and far more stable vacuum tube oscillator. To replace the mica condenser he chose a piezoelectric crystal.

Previously, the piezoelectric effect had had no practical application. A French apothecary, Pierre de la Seignette, of La Rochelle, in 1672 discovered the crystal known as Rochelle salt. In 1880, Pierre and Jacques Curie found that mechanical stresses produced electric charges on the faces of a Rochelle salt crystal. The inverse of this piezoelectric (pressure electricity) effect was theoretically predicted by Lippmann in 1881 and experimentally verified by the Curies the following year—a voltage applied across the crystal produced a change in the thickness of the crystal. Although it was later discovered that many other crystals, including quartz, had this same property, the piezoelectric effect remained nothing more than a scientific curiosity until 1917. In that year Langevin, who became acquainted with the effect while a student in the laboratory of the Curie brothers, applied the output of a vacuum tube oscillator across a quartz crystal to produce the first stable, powerful generator of ultrasonic waves.

Today Langevin's generator, with relatively minor improvements, remains the best source of ultrasonic radiation of precisely controllable frequency and intensity. The high frequency voltage output of a vacuum tube oscillator is applied to electrodes on opposite faces of a properly cut crystal. When the oscillator frequency is adjusted to the natural resonant frequency of the crystal, powerful mechanical vibrations result, and a beam of ultrasonic waves is radiated through the medium surrounding the crystal. In addition to quartz and Rochelle salt, a number of other natural and synthetic crystals may be employed to serve particular applications.

Later Generators

During the decade following the first World War, progress in ultrasonics again slowed to a snail's pace except for certain classified military developments in underwater signaling and the development of the magnetostriction oscillator in 1925 by G. W. Pierce. Pierce used a ferrous metal rod as the core of a solenoid which was energized by an alternating current. As the result of magnetostriction, the ferrous



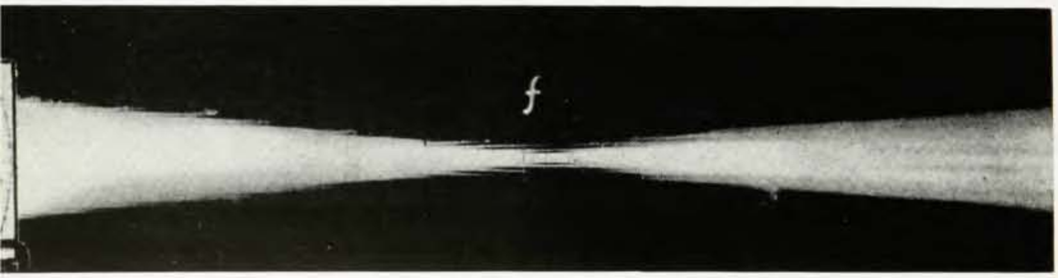
An ultrasonic cell will pass an increasing amount of light to the higher diffraction orders with increasing amplitude of the ultrasonic waves. By using this diffracted light to focus an image of the center plane of the cell on a screen, the Debye-Sears effect is employed here to make visible the diffraction of an ultrasonic beam around a wire 21 sound wavelengths in diameter. Note how the sound reappears in the center of the shadow.

rod periodically changed its length in the alternating magnetic field and a beam of ultrasonic waves was radiated from the end of the vibrating rod. This magnetostriction generator is widely used today, but is limited in the range of frequencies it can generate. For high frequencies the length of the ferrous rod required for resonance becomes too short for practical use, limiting the output of this generator to a maximum frequency of about sixty kilocycles. For higher frequencies the piezoelectric generator has no contender.

It was not until 1930 that nonmilitary ultrasonic research received its first real impetus as the result of the work of R. W. Wood and A. L. Loomis. Wood, who attributed his interest in the subject to the demonstrations he witnessed in Langevin's laboratory at Toulon, imbued Loomis with his own enthusiasm. Alfred Loomis, a wealthy amateur (in the French sense of the word) in the physical sciences, helped Wood set up an elaborate laboratory at Tuxedo Park, New York, where they undertook the first serious, comprehensive study of the physical and biological effects of ultrasonic radiation.

Their apparatus consisted of a disk of quartz resting upon a lead plate at the bottom of a shallow dish filled with transformer oil. The upper surface of the quartz was covered by a thin metal foil, and the foil and the lead plate were connected to the output of a two-kilowatt vacuum tube oscillator. The oscillator was an imposing affair indeed! Consisting of two huge Pliotron tubes, a huge bank of oil condensers, a variable condenser six feet high and two feet in diameter, and an induction coil, it delivered upwards of fifty thousand alternating volts to the quartz transducer.

When the quartz was excited near its resonant frequency, a mound of oil was raised several centimeters above the oil level in the dish and appeared to be in violent agitation. A thermometer immersed in the oil showed only a moderate rise in temperature, but a finger immersed in the oil experienced a scalding pain of considerable severity. When a test tube containing paraffin and water was held in the oil bath, a rapid dispersion of the paraffin in the water took place, yielding a suspension of unusual permanence. Blood corpuscles and other cells of animal or vegetable tissues immersed in a bath in contact with the oil were violently disrupted, and frogs and small fish were quickly killed. A tapering glass rod, half a millimeter in diameter at the tip, with its butt immersed in the oil, transmitted ultrasonic vibrations of such intensity that a chip of wood smoked and emitted sparks when pressed against the tip, the rod burning its way rapidly through the wood. If a glass plate was substituted for the wood, the rod drilled its way through the plate throwing out the displaced material in the form of a fine powder or minute fused globules of glass. The heating occurred only at the point of contact, the remainder of the glass rod being quite cold. These



Focusing of an ultrasonic beam by a plano-convex Lucite lens and the diffraction effect at the focus, f, which is well known in optics.

and a host of other new and interesting effects discovered by Wood and Loomis pointed out the path which has since led into fields of the most surprising variety, interest, and practical importance.

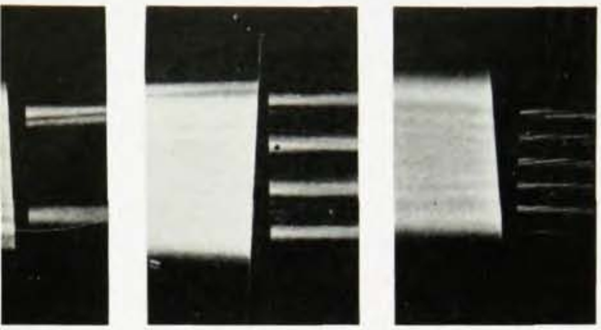
A Tool for Research

A discovery of particular importance was made in 1932 at the Massachusetts Institute of Technology. During the course of a lecture, Professor Paul Debye discussed Brillouin's theory of the dispersion of light and x-rays by heat motion treated as a system of elastic waves at which Bragg reflections take place. Debye predicted that the periodic variations in density in a liquid traversed by ultrasonic waves would give rise to the diffraction of light traversing the ultrasonic field. Professor F. W. Sears, who happened to be in the audience, immediately thereafter set up the experiment. He immersed a quartz plate with metallic electrodes in a glass trough, of rectangular cross section, filled with carbon tetrachloride, and applied a radio frequency voltage to the crystal, thus sending a train of ultrasonic waves down the trough. A source of monochromatic light, a slit, and a lens were so arranged that a parallel beam of light was sent through the liquid perpendicular to the path of the sound waves. After passage through the trough the light was gathered by another lens and, true to the prediction of Debye, formed, instead of a single image of the slit, a beautiful series of its diffraction images. Thus was born the Debye-Sears effect.

The ultrasonic waves in the liquid set up regions of strong compression and rarefaction with different indices of refraction for light. These regions act like a phase grating (echelon) to produce the various diffraction images. From the spacing of the images and the wavelength of the light the sound wavelength can be determined, which, together with the frequency of the sound, permits the determination of the velocity of the sound in the liquid. The measurement of the velocity of ultrasonic waves in a given medium by this method, and by interferometric and pulse methods, permits the determination of various molecular properties which are of interest to both the physicist and the chemist. For example, these measurements permit the determination of the adiabatic compressibility, which, in turn, permits the computation of the specific heat at constant volume, otherwise calculable only by means of complicated thermodynamic relations. From such measurements the relation between the compressibility and the concentration of solutions was determined, permitting the test of a number of interesting questions in the modern theory of electrolytes. Theory predicted that the molar compressibility of electrolytes should vary as the square root of the molar concentration, a prediction that was confirmed by these ultrasonic methods. The measured variation of the velocity of sound with frequency, not predicted by classical theory, leads to a determination, via quantum statistics, of the lifetimes of the excited vibrational states of various atoms and the collision efficiency for excitation.

Ultrasonic waves are also used to set up space transmission gratings in transparent solids, which then scatter light in the way that crystal atoms scatter x-rays, resulting in diffraction patterns similar to those of x-ray Laue patterns. Measurements made on these patterns permit the evaluation of the longitudinal and shear velocities of sound in the solid, and hence of the elastic constants of the medium. Similar measurements permit the determination of the photoelastic constants of the material with greater precision and far less work than was entailed in the older interferometric methods. It should be clear from the foregoing that ultrasonic research can be expected to be of use to the molecular physicist, who ordinarily relies upon light or intense electric and magnetic fields to produce disturbances which he can measure. In ultrasonics he has a new agent, a mechanical one, with which to work.

As the intensity of the ultrasonic waves in the liquid diffraction cell is increased, more and more light is forced from the zero order into the diffracted images, and at a certain sound intensity all of the light is removed from the zero order. If a slit is used to permit only the zero order light to pass, the amount of light passing through the slit can be controlled by the intensity of the ultrasonic waves. Ultrasonic cells, which thus act as light valves, have been used as the light-modulating element in sound-on-film recording systems and in the British Scophony system of television. Furthermore, if stationary ultrasonic waves are set up in the cell by reflection, the diffraction effect is intermittent, with double the frequency of the sound, the sound wave grating being created and destroyed twice each cycle. Light passing through the exit slit is then modulated with this frequency and can be used to give stroboscopic illumination with considerably better light output, simpler construction, and lower



ransmission of a wide ultrasonic beam through aluminum dges of increasing taper. Transmission occurs only where e wedge thickness is such as to give internal resonance.

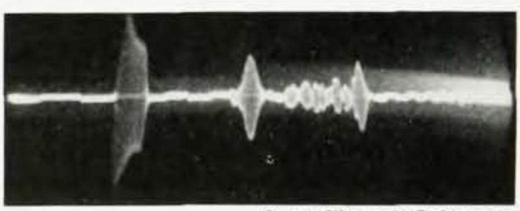
Reflection of an ultrasonic beam from a cylindrical brass reflector.

electrical losses than the widely used Kerr cell. A drawback, however, is the fact that the modulation frequency depends upon the resonant frequency of the particular crystal used and hence is not continuously variable. Still another slight change in the optical system, the addition of a lens to focus the central plane of the cell on a screen, permits the actual shape of the sound beam to be made visible. Very clear photographs of the reflection, refraction, and interference of ultrasonic waves can thus be obtained.

A Few Applications

Since the pioneer work of Wood and Loomis, each year saw new progress in ultrasonics. University and industrial laboratories investigated the potentialities of the new field from various directions. Navy interest in sonar also stimulated ultrasonic research, and both the Navy and the Army Signal Corps sponsored investigations of the properties and effects of high frequency sound. The results of these investigations indicate the unusually wide applicability of ultrasonics.

A pulse technique has been developed for the location of flaws in metals and other solid materials. A crystal is used to send a short pulse of ultrasonic waves into the object to be tested. The same crystal is used (through the direct piezoelectric effect) to receive reflections of the primary pulse. The amplified electrical output of the crystal, portrayed on the screen of a cathode-ray oscilloscope, depicts the primary pulse and all reflected pulses. Reflections caused by flaws permit the presence and location of imperfections to be detected. This technique possesses advantages over x-ray testing in that the equipment is portable, and far greater depths of material can be penetrated. Masses of raw materials can be tested to avoid the machining of defective material, and periodic fatigue checks can easily be made on parts which are under strain as they work without the dismantling of the machinery. One major rubber company tests its entire output of tires by such ultrasonic methods.



Sperry Ultrasonic Reflectoscope

Transmitted Pulse   Defect   Back Edge

The violent agitation produced by high intensity sound waves has a marked dispersive effect on solids and liquids in liquids, producing true colloidal solutions and fine emulsions. By means of ultrasonic irradiation while in the molten state, alloys can be produced of metals such as iron and lead which are ordinarily not miscible in the liquid state. New bearing materials have been made in this way. By such means it has also been possible to produce photographic emulsions of improved homogeneity, stability and sensitivity. The homogenization of milk through ultrasonic irradiation is today an industrial process. The coarse crystals of sulfathiazole have been broken down by ultrasonics to form a creamy emulsion which can be injected through fine hypodermic needles, a technique which was previously impossible.

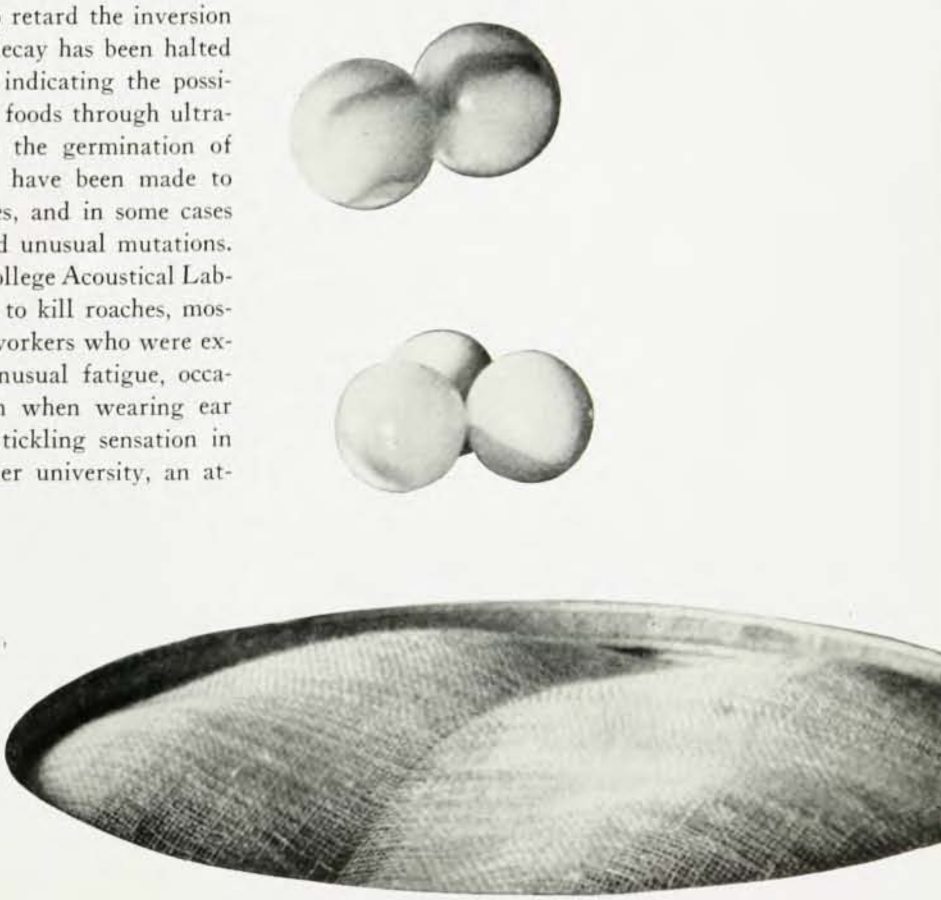
In spite of the fact that ultrasonic waves have this strong dispersive effect on hydrosols, their effect on aerosols is exactly the opposite—namely, coagulation. Irradiation by intense high frequency sound causes almost immediate agglomeration and precipitation of the solid and liquid particles in mist and smoke. At an installation in Kingsmill, Texas this technique is used to recover carbon black from a smokestack. At the Naval Landing Aids Experiment Station, Arcata, California intense sound has been used in this way to turn heavy fog to rain.

Chemical reactions can also be influenced by ultrasonic irradiation. Certain reactions are accelerated, and even depolymerization can be brought about. The chain molecule of starch has been broken down into several fragments to produce dextrine, and gum arabic and gelatine have been decomposed. The aging of whiskey by ultrasonics has been proposed, inasmuch as in the aging process there is a gradual change in the structure of complex molecules, a change which perhaps could be accomplished much more rapidly by sound irradiation.

The biological effects of ultrasonic waves are of particular interest. In several cases the radiation has produced marked diminution in the virulence of bacteria. Yeast cells lose their power of reproduction, luminous bacteria lose their luminosity, and the mosaic virus of tobacco is powerfully deactivated. However, the growth of colon bacilli cannot be influenced even by long exposure to high intensity sound. The bacteria in milk can be destroyed, permitting pasteurization at low temperatures. Experiments undertaken by sugar refiners show that the enzymes in sugar syrup can be destroyed to retard the inversion of sucrose into glucose. Food decay has been halted for as much as several weeks, indicating the possibility of sterilization of canned foods through ultrasonics. The time required for the germination of seeds has been changed, genes have been made to mature at abnormally fast rates, and in some cases genes have been altered to yield unusual mutations.

At the Pennsylvania State College Acoustical Laboratory an ultrasiren was used to kill roaches, mosquitoes, and mice. Laboratory workers who were exposed to the sound reported unusual fatigue, occasional loss of equilibrium even when wearing ear protectors, and a disagreeable tickling sensation in the mouth and nose. At another university, an attempt is being made to focus ultrasonic waves inside living tissue in order to produce the destruction of cells in localized regions. The treatment of deep-seated tumors with x-rays irradiates not only the tumor but the intervening tissues as well. Focused ultrasonic radiation may possibly avoid the over-all destructiveness of x-rays. Only further research can show whether this technique is feasible.

Whereas the field of ultrasonics is a logical extension of low frequency acoustics, the higher frequency range provides a new tool which can bring new aspects of nature into view. It is rare for a physical phenomenon to have found within a few decades such wide application in science and industry. In a broad survey such as the foregoing, it is manifestly impossible to portray the great variety of detail which has been developed in ultrasonic research, and only a few of the interesting problems and applications have been mentioned. Non-military research in this field is still in its infancy, and many of the observed effects have as yet no adequate explanation. Ultrasonics today, a broad and beckoning field for research, holds forth the promise of exciting new discoveries just beyond the horizon.



Five solid glass marbles suspended in space by sound waves from a high intensity ultrasonic siren which are beamed against a reflecting board. Courtesy Harold K. Schilling, Pennsylvania State College.