unsolved problems in ACOUSTICS

By ***R. B. Lindsay***

THE progress of science may be said to depend largely on our asking the most appropriate questions and hoping that the same kind of imagination that led to the questions will provide clues to the answers. There was a time, not so long ago, when it was felt that all possible appropriate fundamental questions about sound had been raised and that the answers indeed were all found in Lord Rayleigh's famous *Theory of Sound*. It was believed to be sure that there were hosts of engineering applications of acoustics to be explored, but that these would not turn up anything fundamentally new. This view is no longer held by those who have followed trends in acoustics during the past quarter century. Both as an active branch of physics and as a subject fundamental to modern engineering, acoustics poses many unsolved problems of fundamental character. Some of these indeed have been suggested by the very advances in instrumentation made possible through acoustical engineering. For it is only through such instrumentation that we can now work with sounds of the very high intensity and high frequency which produce curious and unexplained effects in matter under extreme conditions of temperature and pressure. At the same time it is also through experimental facilities of this kind that we can begin to study more effectively the influence of sound on human beings and other organisms, and this too immediately raises hosts of questions. Through the fertile interplay of theory and application, acoustics is in a particularly strategic position to suggest problems whose solution will cast new light on both the properties of matter and the interaction of sound and man.

The Acoustical Society of America at its 54th meeting at the University of Michigan in Ann Arbor on October 25, 1957, explored some unsolved problems in acoustics in a special symposium. Eight well-known experts reviewed the principal fields of contemporary interest. A brief survey of their remarks is presented in this article.

SINCE to have sound to talk about one must first produce it and then ultimately detect it, it was appropriate that the symposium began with a discussion of transducers. F. V. Hunt of Harvard University pointed out that though progress in the generation of sound waves over wide ranges of frequency and intensity has completely transformed acoustics in the past quarter century, sound producers are still afflicted with serious shortcomings. One of the worst of these is the relatively low electroacoustic conversion efficiency; even for the most commonly used transducers, i.e., the piezoelectric, magnetostrictive, and electrodynamic types, this efficiency rarely reaches 70%. Moreover, even this figure is attained only for very narrow frequency bands. It is an unsolved problem of major proportions to develop transducers which over wide frequency bands will be as efficient as conventional electric motors and generators. Dr. Hunt emphasized the difficulty inherent here in the inevitable mismatch between the hardware of the transducer and the acoustic medium (usually a fluid) into which the acoustic energy is to be fed. Possibly we ought to pay more attention to the successful efforts of electrical amplifier designers to overcome an analogous difficulty in their field. Moreover we ought not to overlook the direct transfer of thermal or electrical energy to acoustic in a liquid or a gas, so as to bypass the intermediary of the vibrating membrane or plate whose behavior has so far taxed to the utmost the standard mathematical techniques. The latter, of course, also balk at the nonlinear behavior exemplified by large-amplitude oscillations. Here it appears we have not sufficiently exploited the capabilities of the large, high-speed computers.

From the standpoint of applied electroacoustics a vital unsolved problem is the economical production of an effective loudspeaker. Dr. Hunt commented that the trouble here is in deciding just what we mean by an

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"effective" speaker; to solve the problem we must ask the right question!

PROBLEMS in sonic engineering, which covers acoustic methods and devices over all accessible frequency and intensity ranges for use in processing, testing, and analyzing materials of all kinds, were reviewed by T. F. Hueter of Raytheon. His remarks fitted beautifully into the content of the previous paper, since he pointed out that many of the unsolved problems in this field are traceable to the inadequacy of available transducers. In fact, the demands often seem to contradict the well-known physical properties of materials: thus the transducer engineer would like to have a good electrical insulator which also is a good conductor of heat! Nature does not always cooperate. Perhaps this is after all a good thing, since it challenges the imagination to look out into new directions.

As an illustration of an engineering application which demands much more basic research for its successful exploitation, Dr. Hueter pointed to chemical processing by means of acoustically induced cavitation. Here we obviously need to learn much more about the dynamics and thermodynamics of the phenomenon itself than we now know. Thus increase of the cavitation threshold with frequency is still a puzzle and makes difficult a valid assessment of one very practical problem encountered in sonic cleaning—whether it is more efficient to employ low-frequency sound at low intensity than high-frequency sound at high intensity.

To get an idea of the demands that the sonic engineer would like to put on the transducer materials needed for his problems the reader might ponder Dr. Hueter's definition of an ideal material as one which "would have the linearity of ADP, the mechanical strength and low electrical impedance of nickel, the temperature stability of quartz and the manufacturability of barium titanate". What a challenge to the solid-state physicist!

THIS challenge will of course be taken up by the solid-state physicist in his own way and not necessarily in the most obvious or direct way. As R. W. Morse of Brown University, the next speaker in the symposium, pointed out, the most fascinating problems in the acoustics of solids of the immediate future would appear to lie in the use of elastic waves to study the fundamental properties of solids under the greatest possible variety of external conditions. The particular area of greatest promise is exploration with extremely high-frequency radiation. Professor Morse reminded his audience that sound waves of frequency 10 000 megacycles in solids have wave lengths of the order of that of visible light and this at once suggests the desirability of extending the acoustic frequency range by a factor of 10 from the present practicable upper limit of about 1000 megacycles. The phonon energy $h\nu$ would then become of the order of 4×10^{-5} electron volt, quite capable of inducing quantum transitions in atoms, as indeed has already been shown to be possible for the lower frequencies now available in the case of nuclear-spin transitions by Tanttila and his co-workers.

A very interesting result of the use of ultrasonics in solid-state physics would be realized if one could make the phonon energy $h\nu$ equal to the thermal energy kT. This might be feasible at liquid helium temperatures (say around 1°K). In a superconductor in which the ultrasonic absorption drops abruptly at the transition temperature T_c because of the energy gap in the distribution of electron energy states around the Fermi level, increase to much higher frequency would have the effect of shifting the onset of absorption decrease to a slightly lower temperature and making it less abrupt.

The possible role of ultrasonics in clarifying our understanding of superconductors was also stressed in terms of the thermal conductivity of crystalline metals, part of which is at all temperatures due to the vibrations of the crystal lattice which constitute phonons of hypersound, though most of it at ordinary temperatures is attributable to the conduction electrons. Below T_c in a superconductor, however, what may be called the "acoustic" contribution to the thermal conductivity can far exceed the conduction electron contribution. The former is readily calculated for any particular frequency dependence of the sound absorption coefficient α. Thus if the dependence is a linear one, the thermal conductivity varies as $T^2/v^2 \times \nu/\alpha$ where v is the velocity of longitudinal elastic waves in the crystal. Comparison of the calculated thermal conductivity on this basis (using Morse's values of ν/α for superconducting tin) with the experimentally determined values (due to Laredo) in the same temperature region shows gratifying order of magnitude agreement. The whole field obviously cries for detailed exploration.

IT is generally agreed that the structure of liquids poses more difficult problems for the physical scientist than that of gases and solids, which may be taken to exemplify the extremes in the scale of orderly arrangement and motion of the constituent molecules. Liquids lie somehow in between: though the distribution of molecules displays a certain amount of order, it is of the short-range variety and fluctuates with time, with numerous holes present in the liquid lattice. By the usual thermal agitation the arrangement of the molecules in the lattice surrounding any given molecule changes with the time, and the average time during which any changed configuration is restored to its original state is called the relaxation time. Now a density fluctuation such as may be produced by a sound wave will promote these structural rearrangements and feed part of the translational energy produced by the sound into them, thus leading to acoustic absorption. If the sound wave is harmonic and its period is equal to 2π times the relaxation time, this absorption (in one wave length) will be a maximum. Hence the study of sound absorption yields a clue as to the relaxation times of structural rearrangements taking place in liquids. Theodore Litovitz of Catholic University of

America reviewed this problem of structural relaxation in liquids and called attention to the fact that in using acoustical waves to probe the structure of liquids (or indeed any phase of matter) the acoustician is really a sonic spectroscopist. Just as the optical spectroscopist uses a wide frequency range of electromagnetic radiation to study the energy states of atoms with respect to their extra-nuclear electrons, so the acoustic spectroscopist uses acoustic energy to disturb the distribution and energy states of molecules, particularly with reference to the liquid lattice.

But, as Professor Litovitz stressed, though many data on acoustic absorption and dispersion in liquids exist, the theory of structural molecular relaxation is still in a primitive state. In general only two-state relaxation processes have been studied, whereas it is fairly sure that the actual changes are more complicated. Moreover, Nature is rather unkind to us in that the relaxation frequencies of the simpler types of liquids which are amenable to theoretical treatment lie beyond the frequency limits now available for experiment and hence render experimental tests of any given theory very difficult if not impossible. This is another powerful argument in favor of the experimental realization of much higher ultrasonic frequencies.

Professor Litovitz has made some interesting comparisons of dielectric relaxation times with acoustic relaxation times and has found that in the case of long-chain molecules with hydroxyl groups bonded to carbon atoms the ratio of the dielectric relaxation time to the acoustic relaxation time increases rapidly as the relative number of hydroxyl groups decreases. This might well appear to add a paradoxical note to the whole problem, since the smaller the relative number of hydroxyl groups, whose rotation around the chain is principally involved in dielectric relaxation, the easier should be the rotation and the shorter the relaxation time; on the other hand the acoustical relaxation time would be expected to remain more or less the same if the process is one merely of rearrangement of the molecules as a whole.* The question is indeed a fascinating example of an unsolved problem in the liquid state in the solution of which acoustics will undoubtedly play a considerable role.

PASSING now from what has come to be called physical acoustics, we consider some fundamental problems in applied acoustics. Probably the one that affects the greatest number of people most of the time is that of noise. We live in a sea of noise and most of us would prefer to have less of it. Calling attention to the fact that steady-state noise has now been studied for many years and much is known about its reduction in rooms, etc., R. O. Fehr of the General Electric Co. pointed out in his review that the problem of impact noise is much more difficult. This is unfortunate since it is from precisely such noises (e.g., those from jet engines, trains, automobiles, and even domestic machinery) that much of our more recent troubles arise. Though it is difficult even to describe analytically an impact force, involving as it does a variable and usually complicated distribution of energy as a function of time, some progress has been made in the airplane problem by increasing the impedance of the fuselage panel. But the engineer has economic as well as purely scientific questions to face in this matter. Its urgent character is pointed up by the fact that mechanical strength as well as acoustical noise is involved. Dr. Fehr emphasized the importance of developing equipment for the accurate measurement of total sound power in an acoustic field in order that meaningful noise specifications may be written and enforced.

Closely related to impact noise is the whole problem of the reaction of engineering structures to shock. One of the great difficulties is the representation of a complicated structure by an adequate physical model whose response to shock can be put into a mathematical form that can be handled even by present-day computers. Some progress has been made along this line, however. On the practical side, moreover, experimental tests are well known for studying damage under shock. They have the drawback that they may lead to over-design of parts of the equipment and hence be uneconomical.

Dr. Fehr pointed out that one must not overlook the importance of vibration "noise" in machinery, particularly its influence on smooth and safe performance. Here the analytical problems involved are far from solution.

EVER since the early experiments some thirty years ago on the lethal effect of intense ultrasound on bacteria and small animals like frogs and mice, there has been a steadily growing interest in the biological action of sound radiation. W. J. Fry of the Bioacoustics Laboratory of the University of Illinois presented a survey of some aspects of this field with particular reference to problems as yet unsolved. As he pointed out, acoustic radiation can interact with a biological system in many different ways. Thus at low intensity, an ultrasonic beam may be reflected from the interface of tissues with different physical properties and hence serve as an identifying tool; its absorption by tissue may serve the same purpose. On the other hand, if it is sufficiently intense the sound may produce selective disruption of structure, for example through the weakening of bonds in giant macromolecules. Such disruption may affect very considerably the subsequent behavior of the cell which is the seat of these molecules. Professor Fry mentioned some recent Russian experiments indicating the possible use of intense ultrasound for the destruction of malignant tumors. This possible application of ultrasonics to the cancer problem of course awaits much further exploratory work, but at least it illustrates that acoustics may prove to be a far more valuable tool in medicine than has been previously suspected, though clinically many successes, par-

* It has been pointed out by Professor R. H. Cole of the Department of Chemistry in Brown University that this last assumption may not indeed be well founded: the longer chain molecules with a relatively smaller number of bonded hydroxyl groups may well show greater ease and flexibility in rearrangement and hence lead to smaller acoustical relaxation times.

ticularly in the treatment of such disorders as arthritis, have been reported.

The diagnostic employment of ultrasound has been a great challenge due to the relatively small energy reflected from soft tissues and the lack of resolution except at very high frequencies which suffer large absorption. However, Professor Fry mentioned the recent success of D. Howry of the University of Denver in securing ultrasonographs of human tissue which rival x-ray pictures in clarity and can indeed be obtained under conditions for which x rays are of no use. The ultimate possibilities here seem only restricted by the elaborateness and expense of equipment. Even the microstructure of living cells is amenable to study by this method through the construction of an ultrasonic microscope. Cellular structure like the distribution of proteins may be elucidated by these means.

Professor Fry's own extensive contributions to the study of the central nervous system by the use of sharply focused ultrasound should not go unmentioned. He has shown that it is possible to destroy selected neural components while the surrounding vascular system is undisturbed. The possibilities for neurosurgery even in humans are fascinating.

WE cannot forget that the original meaning of the word "acoustics" is "hearing". The subject has come a long way from its primitive concern and yet in a day in which both relativistic and quantum physics puts increasing stress on the role of the observer, we ought not to overlook acoustical observation from the standpoint of the human being. Merle Lawrence of the University of Michigan divided his survey of unsolved problems in hearing into three areas: (1) the actual phenomena of hearing, (2) theories of hearing, and (3) physiological and psychological variations accounting for individual differences. Pointing out what an enormous variety of material there is available in each group, he confined himself to three illustrations. The first relates to tinnitus or ringing in the ears experienced by a person exposed for a long time to a rather intense noise, and often leading to a serious handicap in the performance of ordinary business duties. In the attempt to understand this, an experiment was tried in which an observer was subjected to binaural beats while performing some task. It was found that the performance was seriously affected, whereas externally presented pure and beating tones had no such effect. There is at present no answer to the question why this should be so. It is simply an unexplained hearing phenomenon.

One might suppose that the proper recourse in a case of this kind is a theory of hearing. But Professor Lawrence expressed doubt about the sophistication of present theories of hearing. He called attention to the great confidence which Corti a hundred years ago developed in his theory based on his examination of the fibers in the basilar membrane which now bear his name. And yet Corti did not see quite enough. Professor Lawrence suggested that probably we ourselves have not seen quite enough of the structures of the inner ear and their function to justify elaborate theories. The unsolved problem here obviously demands the increasing collaboration of anatomist, physiologist, and physicist.

Finally Professor Lawrence laid stress on the ultimate importance of individual differences in hearing. Whereas the usual psychophysical approach to hearing involves the statistical study of the experiences of many individuals and the attempt to establish a kind of "median" listener, he would raise the question why it is not after all just as important to establish the reasons for the existence of these differences. The practical significance of this in connection with industrial hearing loss is obvious. It also opens up a tremendously wide field of basic research.

THE symposium was appropriately brought to a close by a review of speech and communication by George A. Miller of Harvard University. This is a wide field which only in part overlaps acoustics, but this part is vital in human affairs. Dr. Miller built his talk around a single unsolved problem, namely, that of the possible construction of a machine capable of translation from printed to spoken language and vice versa. The practical value of such an invention needs no emphasis. One of the prime difficulties encountered in the mere consideration of such a device is the rather inadequate state of measurements of speech sound. The first task would be to set up a more accurate specification of individual speech sounds. Individual differences again raise hob with the attainment of this goal, but the speaker felt that they do not render it impossible. An even greater source of difficulty is the now well-established fact that the same acoustic pattern can be perceived by a listener as any one of several different speech sounds (phonemes) depending on its acoustical environment. It is therefore not practicable to work with isolated phonemes and the machine under contemplation must have some memory built into it. Then there is the segmentation problem—the difficulty of telling where one phoneme ends and the next begins. This may be overcome, but how about the corresponding problem for words? How can a machine be made to distinguish, for example, between "an aim" and "a name", to mention one case cited by the speaker? Professor Miller thought we might get valuable information from the way a child learns to read and translate what he has read into speech. Possibly a computer could be programmed to learn the language as a child learns it. Detailed study of the computer might then provide a clue to some of the problems inherent in the construction of the translating machine. No one can doubt that the challenge provided by the acoustics of speech is one of the subtlest in the whole field of sound.

A review of the kind attempted in this symposium on unsolved problems in acoustics is bound to be a highly condensed one and necessarily omits much, but the candid observer must admit that cursory though it is, it shows the "spectrum" of acoustics, pure and applied, to be a very broad segment of physics.