than 1000 seconds in the present example, so that groups of particles must be injected to replenish the beam at a rate not less than the reasonable value of one group per second.

It is the hope of the MURA group that further theoretical and experimental work will lead to the design and construction of models that will permit testing means for efficient particle acceleration, the investigation of high-current beams, and the eventual realization of a research machine that will take full advantage of the benefits to be derived from the FFAG principle.

References and Notes

1. It is impossible here to give explicit credit to the many physicists who have contributed to the development of these ideas, but it is fitting to indicate our special appreciation of the courtesy which the University of Illinois has extended to the MURA group in making the ILLIAC available for numerous computational studies and our indebtedness to J. N. Snyder for directing this phase of the program. I wish also to express my appreciation to D. W. Kerst, K. R. Symon, and A. M. Sessler for assistance in the preparation of this article and to K. Lark-Horovitz for his courtesy in reading the manuscript in draft form.
2. The technical group has been under the direction of D. W. Kerst. As the interest in the work grew, a number of midwestern institutions formalized this cooperative effort by forming the Midwestern University Research Association (MURA). The work of the technical group has been assisted by the National Science Foundation, the Office of Naval Research, and the U.S. Atomic Energy Commission.
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13. R. Christian, unpublished.
14. This relationship was derived originally by A. M. Sessler and me, and it has recently been treated more carefully by G. Parzen, unpublished.
15. In the absence of back-wound currents on the pole surface and with f assuming its optimum value, 0.24, the available magnet gap is limited to $G = 0.28(2\pi w)r = 0.28\lambda$, where λ is the radial wavelength of the magnet structure.
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Sonic Techniques for Industry

T. F. Hueter

Recently an impressive gathering of acoustical scientists and engineers took place in Cambridge, Massachusetts. From 18 to 23 June, more than 800 experts from approximately 20 nations met at Massachusetts Institute of Technology and Harvard University to participate in the second International Congress on Acoustics. Five main themes had been selected for the technical program to represent the major fields of current activity in acoustics. Most of these dealt with more or less familiar problems, such as speech and hearing, sound reproduction and recording, noise control, and wave propagation. A group of five technical sessions, however, comprising about 50 papers, appeared under the collective heading of "Sonics." Most of these papers had very practical implications, the accent being on techniques and applications rather than on studies of acoustic phenomena for their own sake. Sound waves of all frequencies were shown to be useful as a tool in a variety of technical fields quite remote from the customary domain of classical acoustics.

Many participants in these sessions came from industrial laboratories or engineering centers, and it was apparent from the discussions that a new area of technology, based on the use of sound waves, is taking shape. About 2 years ago, R. H. Bolt of M.I.T. and I coined the term *sonics* for this new technology, which encompasses the analysis, testing, and processing of materials and products by the use of mechanical vibrating energy. The particular frequency that is best suited for a given task is determined by the special requirements and limitations of the task. All applications of sonics, however, are based on the same physical principles, and the relation of the frequency used to the range of audibility for man's ear is irrelevant from this point of view.

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Applications

We shall see that the phenomenon of acoustic vibration can be utilized in many ways. With sound waves we can "sonograph" (as with light waves we photograph) the inner structure of bodies that are opaque to light. Sound waves can penetrate many solids and liquids more readily than x-rays or other forms of electromagnetic energy. Thus sound can expose a tiny crack imbedded many feet deep in metal, where detection by any other means might be commercially impracticable if not impossible. Similarly, ultrasonic pulse techniques are now being used in medicine for the early diagnosis of abnormal tissue growths.

By acoustic techniques we can measure the elastic constants of solid materials, and residual stresses or structural changes can be analyzed. The molecular arrangements within many organic liquids can be inferred from measurements of sound velocity or absorption. The rates of energy transfer among gas molecules and the chemical affinity of gaseous mixtures can be determined by using sound waves.

As soon as we can measure a process, we have within reach a means of controlling it. Indeed, acoustic instrumentation offers extensive but virtually unexplored opportunities in the automatic control of industrial processes. The geometry of metal parts, the quality of cast metals and laminated plastics, the temperature in the combustion chamber of gasoline engines, the composition of compounds in the liquid or gas phase, the flow velocity of liquids and gases—these and many other process variables throughout industry may, in time, come under the watchful ear of acoustics.

In the afore-mentioned applications, the sound is used as a measuring stick or flashlight—the amounts of power are small and incidental. In another class of applications, large amounts of acoustic power are employed to do useful work. Vibrational energy is used to drill rock, to machine complicated profiles in one single operation, and to engrave all kinds of jewelry. As a potent microagitator, sound will facilitate the emulsification of liquid mixtures and will speed up such processes as homogenization or dispersion. Sonic cavitation has become a powerful method for the cleaning of precision parts and may find important applications in electrochemistry. Acting on aerosols, such as fumes, dusts, and smokes, sound can speed up agglomeration and collection of particles.

Table 1. Technical fields represented by members of the committee on sonic and ultrasonic engineering of the American Acoustical Society.

Field of commercial activity	Frequency range
Oil-well drilling	20–50 cy/sec
Liquid processing*	0.2–10 kcy/sec
Machining, engraving, and welding	20–30 kcy/sec
Dental drilling	20–30 kcy/sec
Viscosimetry	25–30 kcy/sec
Underwater signaling	2–200 kcy/sec
Cleaning of metal parts	20–700 kcy/sec
Applications in electrochemistry*	20–1000 kcy/sec
Medical therapy	1000 kcy/sec
Nondestructive testing	0.5–15 Mcy/sec
Information storage	10–40 Mcy/sec
Molecular analysis*	Entire range

* Not yet in general industrial use in the United States.

Recently, the Acoustical Society of America organized a technical committee on sonic and ultrasonic engineering. This group had its first meeting during the afore-mentioned International Congress on Acoustics. Its members, comprising economics-conscious industrial engineers and research-minded university physicists, are engaged in the activities listed in Table 1. The frequency range covered by these applications is extremely wide. Their realization therefore entails widely different acoustic engineering practices, which is a characteristic feature—and sometimes a difficulty—of this new field of sonics.

Most of the applications listed in Table 1 have today reached the stage of successful commercial operations; that is, the usefulness to industry of these techniques and instruments has been widely recognized, the development of reliable equipment is more or less completed, and the manufacture, sales, and maintenance of the equipment have proved to be economical.

The three items marked in Table 1 by asterisks—liquid processing, electrochemistry, and molecular analysis—have not yet conquered the market in this country (*1*), although basically they do not appear to be less promising than those which have. In fact, sonic treatment of liquid mixtures and slurries and sonic improvement of electroplating techniques are already in industrial use in Europe. The success of such processing methods depends largely on the availability of transducer mechanisms that are capable of generating sonic power economically, both in sufficient amounts and in a way compatible with the flow of industrial production. If the materials to be treated are encountered in small- or medium-sized batches, conventional transducers of the magnetostrictive or piezoelectric type may handle the job. For example, in the brewery industry such units have been installed for the extraction of vegetable bitters from the hop. They become impractical, however, for very large batches or high rates of liquid flow. In this case, the recently developed hydrodynamic valve oscillators (*2*) (Fig. 1) or some types of liquid jet transducers may be much more adequate. Both are being considered for large scale dyeing, cleaning, and plating operations.

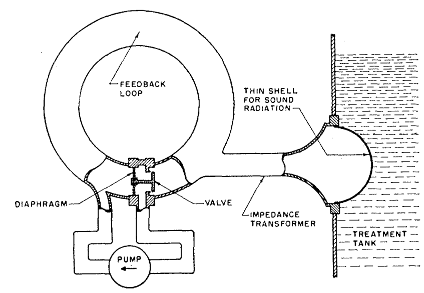

Fig. 1. Hydrodynamic valve oscillator coupled to a treatment tank, according to the method of J. V. Bouyoucos. Direct-current flow energy is provided by a pump. Fluctuations of pressure at the left side of the diaphragm produce a flow modulation owing to changes in the gap area of the valve. The resulting pressure changes at the valve end of the loop are transmitted through the loop back to the diaphragm. Stable oscillations build up at a frequency for which the half-wavelength equals the loop length. Sound energy is extracted from the loop by a transmission-line section terminated by a dome-shaped acoustical window.

Molecular analysis by sonic measurement techniques is a particularly fascinating field. So far, however, it has been exploited almost exclusively by university physicists for purely scientific purposes. They have perfected both the theoretical concepts and the required acoustic instrumentation to a high degree (*3*). It would thus appear that the analysis by ultrasonic interferometry of acoustically excited molecules could well become a valuable adjunct to infrared spectroscopy, which utilizes the electromagnetic radiation emitted or absorbed by molecular vibrations.

We may now ask ourselves why the adoption of sonic techniques has been relatively slow in many areas of industry, despite the impressive list of potentially useful effects that have been described in the literature during the last 25 years (*4*). Some relevant answers to this question were given during the afore-mentioned meeting of the committee for sonic and ultrasonic engineering. They may be condensed into the following three key problems, which seem to pose themselves whenever the applicability to industry of a new tool, or process, or instrumentation is being evaluated: (i) the recognition of an existing need; (ii) the demonstration of technical feasibility; and (iii) the economics of both development and operation.

A clear-cut evaluation of these questions requires a close meeting of minds between the sonics experts, the production engineers, and management—and often a potentially useful approach is abandoned because of the lack of technical liaison. In other cases, the final completion of the development of a process that was shown to be feasible in small-scale laboratory tests did not take place because of excessive costs.

However, sometimes the need, the feasibility, and the economics have been mutually supporting, and a highly successful new instrumentation has emerged. This was the case, for example, in the field of nondestructive testing. Here, the introduction of ultrasonic pulse-echo techniques during the past 10 years (*5*) has filled an urgent need for more sensitive testing methods in a rapidly developing technology (Fig. 2). Moreover, with continued research, the capabilities of the method have been increased beyond the mere detecting of cracks and flaws. It is now possible to evaluate ultrasonically rather subtle material properties such as surface hardness or metal fatigue.

Another example is the use of sonic energy for the cleaning of delicate components of instruments. Conventional methods rely largely on manual manipulation of these parts. As Table 2 shows, the ultrasonic method which does the same job much faster and often more thoroughly, appears to be quite superior from an economic point of view.

But even if the afore-mentioned three basic requirements are met, and a hopeful new product is born, a good deal of continued nursing, mainly in the form of technical education, is necessary to keep it alive and to adapt it to the ever-changing needs of industry. And this again can be achieved only by the cultivation of the relationships between the scientific-minded people in the laboratory and the practical-minded people in the field.

At present the liason between the two groups is far from satisfactory from the point of view of a healthy development of sonic technology. It appears that there are two main reasons: one is the general shortage of trained manpower in applied physics; the other is the need for more interdepartmental training programs at our universities and colleges. Vigorous educational programs already exist in nuclear engineering, they are being considered in molecular engineering (*6*), and they should be initiated in sonics.

Table 2. Analysis of monthly cleaning and repair costs (*10*). The numbers in parentheses in column 1 indicate the quantity.

Assembly	Old method	Ultrasonic
2 CM75 field coil (8)	$1016	$ 408.20
2 CH75 armature (4)	480	198.98
30 E02 field coil (8)	995	451.20
30 E02 armature (8)	928	512.20
1193 field coil (8)	920	336.20
1193 armature (4)	440	236.10
901 field coil (5)	400	128.13
Total monthly cost	$5179	$2271.01

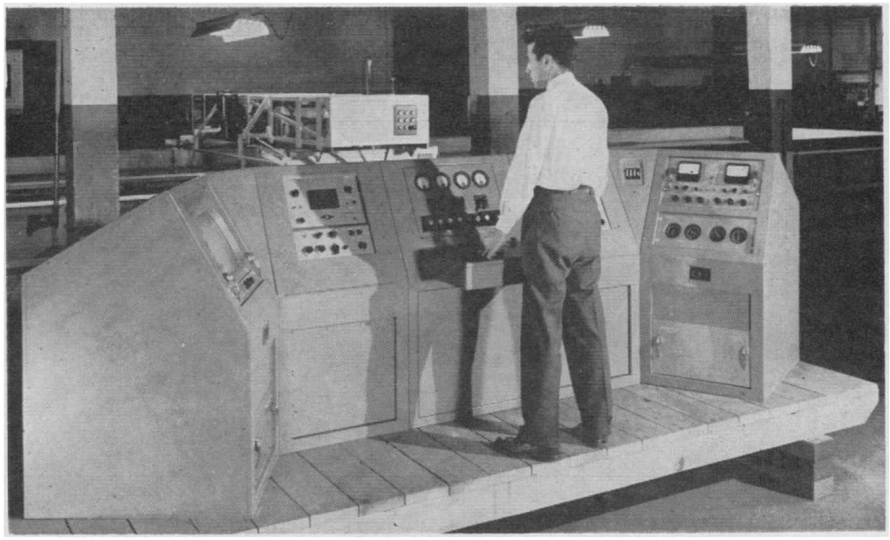

Fig. 2. Ultrasonic inspection system at Lockheed Aviation Corporation. In the foreground are control panels for programmed scanning. Jet-turbine parts are immersed in the large tank shown in background. The movable bridge astride the tank supports ultrasonic transducer heads capable of following complicated contours.

Basic Physics

Let us now review some of the basic physics underlying the field of sonics. Some examples of the instruments that are currently available for sonic analysis and processing will be described as we go along.

A sound wave is characterized by its speed of propagation and its velocity. In solids, the velocity c is

$$c = \sqrt{\frac{E}{\rho}}$$

where E is the elastic modulus and ρ is the density; in liquids, the velocity is

$$c = \sqrt{\frac{1}{\beta\rho}}$$

where β is the adiabatic compressibility; in gases, the velocity is

$$c = \sqrt{\frac{P_0\gamma}{\rho}}$$

where P_0 is the ambient pressure and γ is the ratio of specific heats.

The wavelength then is $\lambda = c/f$, where f is the frequency of sound—for example, in water ($c = 1500$ m/sec) it is about 5 centimeters at 30 kilocycles per second and about 1.5 millimeters at 1 megacycle per second. In steel, the respective wavelengths are about 4 times as large. The particles in a medium exposed to sound oscillate around their equilibrium positions with a maximum displacement (amplitude) A, a maximum velocity $U = \omega A$ (where the angular frequency $\omega = 2\pi f$), and a maximum pressure $P = \rho c U$. The ratio $P/U = \rho c$ is called the characteristic impedance of the medium, and the product

$$\frac{P \times U}{2} = \frac{\rho c \omega^2 A^2}{2}$$

is the sound intensity. This important quantity is expressed in watts per square centimeter; it may be as low as 10^{-3} watts per square centimeter in analytic sonics and as high as 10^3 watts per square centimeter in sonic processing.

Sound waves may be generated by moving diaphragms or pistons, by devices that interrupt a fluid flow (sirens, jets, valve oscillators), or by slabs of materials that contract or expand under the influence of magnetic or electric fields. Usually the use of each type of transducer is limited to a certain frequency range. It is therefore an important task of the sonic engineer to determine, first, the optimum frequency range from the point of view of the end-result to be achieved and, second, to pick the type of transducer that is most efficient in this range.

Another important quantity is the sound absorption of the medium. It determines the range of penetration of the wave and depends greatly on the homogeneity and structure of the medium.

After this brief survey of acoustic terminology, we are ready to proceed with a discussion of the basic principles involved in (i) the use of sound waves in testing and analysis, and (ii) the processing of materials by sonic energy.

Table 3. Types of waves in isotropic solids.

Item	Pure longitudinal (bulk waves)	Pure transverse (shear waves)	Extensional (rod waves)	Flexural (bending waves)	Surface (Rayleigh waves)
Boundary requirements	Infinite	Infinite	Finite	Finite	Infinite
Dimensions of sample	$d \gg \lambda$	$d \gg \lambda$	$d \leqq \lambda$	$d < \lambda$	$d \gg \lambda$
Modulus of elasticity	$\lambda' + 2\mu$	μ	Y	Dependent on λ and d	Dependent on μ and σ
Sound velocity	$\sqrt{(\lambda' + 2\mu)/\rho}$ $\sqrt{\frac{Y}{\rho}\frac{1-\sigma}{(1+\sigma)(1-2\sigma)}}$	$\sqrt{\mu/\rho}$ $\sqrt{\frac{Y}{\rho}\frac{1}{2(1+\sigma)}}$	$\sqrt{Y/\rho}$ $\sqrt{\frac{\mu}{\rho}\frac{3\lambda' + 2\mu}{\lambda' + \mu}}$	Rod of radius r: $\sqrt{\omega r/2} \times \sqrt[4]{Y/\rho}$ Plate of thickness d: $\sqrt{\omega d/2} \times \sqrt[4]{\frac{Y}{\rho}\frac{1}{3(1-\sigma^2)}}$	$\frac{0.87 + 1.12\sigma}{1+\sigma}\sqrt{\mu/\rho}$
Wave-type conversion at boundary	Partly to shear wave	Partly to bulk wave	To Rayleigh wave as $\lambda \ll d$	To Rayleigh wave as $\lambda \ll d$	

The two quantities that are fundamental to all measurements are the sound velocity c and the sound attenuation coefficient α, and the solutions of the wave equation are of the form

$$y_x = y_0 \exp. j(\omega t - k^* x)\,;\; k^* = \frac{\omega}{c} - j\alpha$$

where y may represent any of the field variables, such as particle displacement, particle velocity, or pressure, and k^* is the complex propagation constant.

The response of matter to elastic strains, such as those occurring periodically in a sound wave, is intimately related to the interactions between the building blocks of matter, the atoms, molecules, or ions. In the case of solids, stiffness may be related directly to the lattice forces, as is suggested by the Grueneisen rule (7). In liquids, the compressibility is proportional to the molecular packing factor s = (molecular volume)/(molar volume): c_{liq} = const. × s, where const. ≃ 5000. In gases the decisive factor in sound propagation is the ratio of specific heats

$$\gamma = \frac{c_p}{c_v} = \frac{f+2}{f}$$

where f is the number of degrees of freedom of the gas. The sound wave propagates by transmitting momentum from molecule to molecule through collisions. In this process, internal molecular vibrations are excited to a degree that depends on the number of effective collisions within each cycle of the sound wave. As a result, the quantity f and with it the effective magnitude of γ may vary with the sound frequency. The time constants involved in the energy transfer by collision depend largely on the presence of impurities in a gas. This suggests the use of sound velocity measurements for gas analysis (Fig. 3), as for example by ultrasonic interferometry.

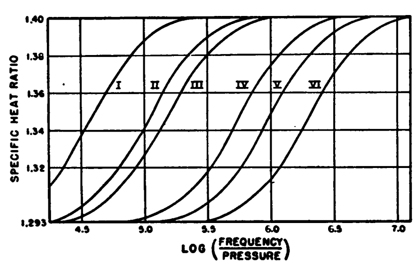

Fig. 3. Influence of impurities on sound velocity in carbon dioxide, according to A. Eucken and R. Becker. I, pure CO_2; II, CO_2 and 5 percent He; III, CO_2 and 11.3 percent CH_4; IV, CO_2 and 5.7 percent H_2; V, CO_2 and 12.3 percent H_2; VI, CO_2 and 2.8 percent H_2O.

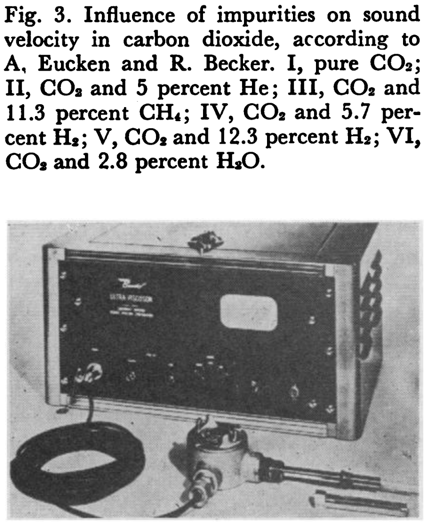

Fig. 4. Ultrasonic viscosimeter. The transducer consists of a longitudinally vibrating magnetostrictive reed. [Courtesy Bendix Aviation Corporation]

Time-dependent adjustments of internal molecular excitation (in gases) or of external molecular configuration (in liquids) to applied compressions are referred to as relaxation processes. Configurational relaxation takes place in certain organic solutions, in electrolytes, and in suspensions of high polymer, long-chain molecules. At those frequencies where relaxation occurs, characteristic changes of sound velocity and sound absorption may be observed. Also, the rheological properties of viscous liquids and slurries may be analyzed acoustically by means of shear waves and by using the characteristic reaction of a medium on a sound source. Measurement of the impedance offered by a "loaded" shear transducer to its associated electric network will thus allow a determination of the complex shear rigidity of the loading medium. Instruments based on such shear-wave impedometry are now commercially available (Fig. 4). Their applications range from the control of petroleum fractionation to the evaluation of blood clotting times.

Techniques

We shall now consider some of the techniques that are used in sonic analysis. For the measurement of sound velocity or wavelength there are two methods of

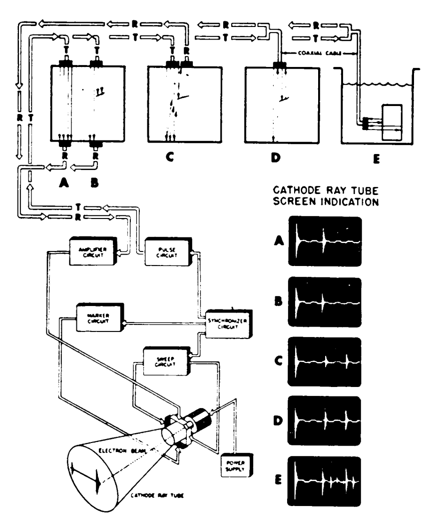

Fig. 5. Ultrasonic pulse techniques. (*A*, *B*) pulse transmission from transmitter crystal T to receiver crystal R; (*C*) pulse reflection method with separate crystals T and R; the extra pip on the oscilloscope indicates a flaw; (*D*) pulse reflection method with a single crystal for T and R; (*E*) immersion technique; the oscilloscope pattern shows multiple reflections between sample boundaries. [Courtesy Sperry Products, Inc.]

choice, standing-wave techniques and pulse techniques. In standing-wave techniques, the periodicity in space of one of the acoustic field variables—pressure, density, or particle velocity—is determined. Typical devices that are widely used are the acoustic interferometer and the impedance tube (*8*). In pulse techniques, the time required by a short wave train to travel a given distance is measured. Standing-wave techniques are usually more suitable in the kilocycle range of frequencies, whereas pulse techniques are indicated for the megacycle range. The various ways in which ultrasonic pulses may be used to detect flaws in solids or to measure thicknesses or distances are illustrated in Fig. 5. Similar techniques are used for gaging the level of liquids in closed tanks, and pulses reverberating many times in a suitably shaped solid block serve as information storage devices.

At this point we must note that, whereas only one type of wave—namely, longitudinal—exists in gases, additional forms of wave propagation are possible as the rigidity and structure of matter change. We have already mentioned that liquids of high viscosity may support shear waves in addition to longitudinal waves. In isotropic solids we must distinguish between five different types of waves (Table 3). Finally, anisotropy will lead to a dependence of sound velocity on the direction of propagation, with regard to the crystal axes.

If the variation of pressure and the density in a sound wave are in phase, the wave propagates without loss of energy. However, once the period of the sound vibration is comparable with the time constant of one of the afore-mentioned relaxation processes, the density will lag behind the pressure. The loop area of the resulting pressure-density diagram then represents the energy that is lost per cycle. Another cause of losses is multiple reflection or scattering that is caused, for example, by grain boundaries in polycrystalline materials. In principle, such losses may be determined in four different ways, as is illustrated in Fig. 6. They are (i) the time decay of forced vibrations in a standing-wave system, (ii) the decrease in amplitude with distance in progressive waves, (iii) the bandwidth of a harmonic mode of a resonating system, and (iv) the standing-wave ratio in an impedance tube. Many technical materials have been analyzed by these methods, and useful correlations have been established between their loss behavior and other physical properties.

We now come to the other application of sonics—namely, the processing of materials. It has been found that intense vibrations affect colloidal distributions, equalize electrolytic concentrations, and speed up aging processes. Also, by ab-

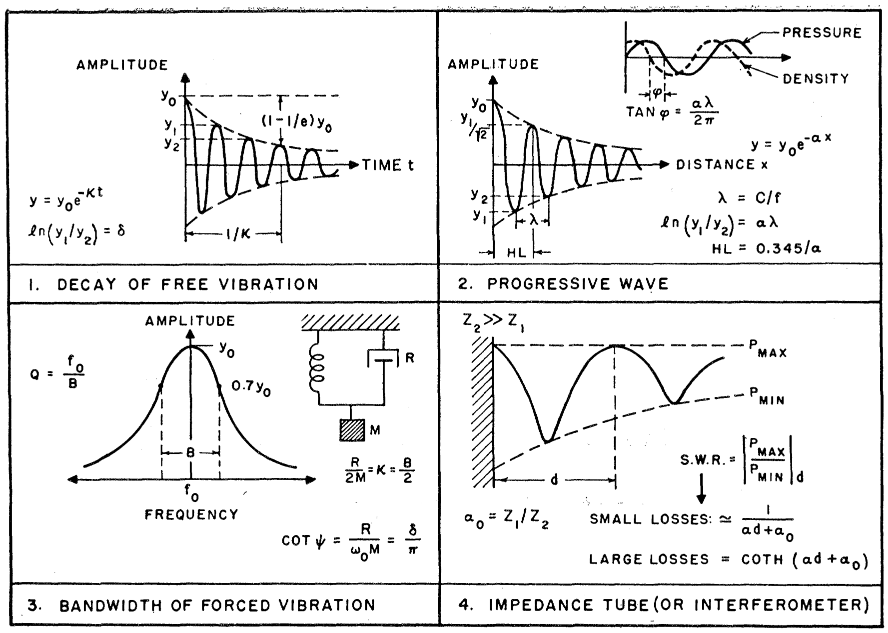

Fig. 6. Basic techniques for attenuation measurements: κ, temporal damping constant; α, spatial attenuation constant; δ, logarithmic decrement; Q, quality factor, S.W.R. = standing-wave ratio.

sorption in a lossy medium, intense vibrations may produce local heating effects as, for example, in the use of ultrasonics in medical therapy. In general, one may distinguish between two types of action, effects that are localized at interfaces between different kinds of media or between constituents of the same medium, and volume effects. Interface effects play a predominant role in power sonics and lead to a number of unusual phenomena. They are produced more readily than volume effects. For example, small bubbles or particles suspended in a liquid are subjected to drag forces in a sound field; similar forces come into play if a sound field interacts with an aerosol. This, then, is the physical basis for such processes as sonic stirring, degassing, and coagulation.

A particularly powerful phenomenon is cavitation. This is the breakdown of the cohesion of a liquid that is exposed to high tensile forces as the sound wave passes through it. Such breakdown usually occurs at the weakest points within

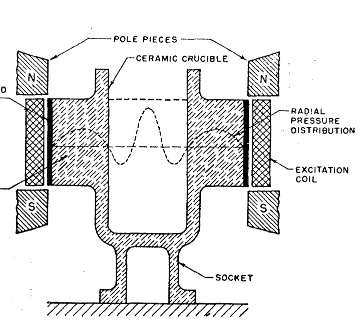

Fig. 7. Vibrating crucible for irradiation of metal melts, according to H. Seemann.

the liquid. Tiny bubbles, dust particles, and particularly interfaces where poor wetting conditions exist, facilitate the onset of cavitation. As the term cavitation implies, cavities are formed in a liquid during the negative pressure phase of the sound wave; these subsequently collapse during the positive pressure phase. Such cavity collapses may produce pressure peaks of several hundreds of atmospheres. Under the influence of cavitation, steel surfaces may be pitted, oxide layers removed, bacteria disintegrated, or high polymers depolymerized. One particularly successful application of surface cavitation is in ultrasonic drilling; another is in the soldering of aluminum.

The periodic strains set up by intense vibrations in metals or solidifying melts (*9*) are capable of rearranging dislocations or impurities in some materials. This may have an effect on crystallization, grain formation, and precipitation hardening. A promising electrodynamic method for exciting whole crucibles to intense radial vibrations at frequencies of 10 to 50 kilocycles per second is shown in Fig. 7.

The number of specific examples that could be given in this review of the present scope of sonics is of necessity limited. However, it may give the reader some feeling for the potential usefulness of acoustic instrumentation in certain industrial tasks. It is safe to say that acoustical physicists who are interested in the growth of sonics are eager to accept the challenge of their industrial colleagues to put sound waves to work. Progress during recent years has been encouraging, and with improved contacts among interested parties more valuable contributions of sonics to industry may well be expected.

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New Principle of Closed System Centrifugation

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Owing to its easy availability, blood was one of the first human tissues to undergo definitive chemical study. However, certain of the components have been difficult to obtain in their true state in nature. This often has given rise to conflicting data. The dynamic state of blood within the body, as well as its peculiar property of being able to change from a liquid to a solid, makes the static conditions of blood outside the circulation highly artificial. The early discovery that citrate and other calcium complexing agents would block coagulation has been estimated (*1*) to have slowed certain types of hematologic research by several decades. This is not due to intrinsic damage from citrate ion. Rather, it is because blood rendered incoagulable can be collected without attention to its labile components. This has led to the universal collection of blood, for either analysis or therapy, under nonphysiologic conditions; rubber tubing, warm glass bottles, and anticoagulant solution, followed by a variable storage period during which the equilibrium state of cell destruction and resynthesis no longer obtained.

In an effort to surmount these conditions, work was begun in 1949 by Edwin J. Cohn and collaborators on equipment designed to collect and fractionate blood as early as possible in its natural state. The underlying principles were simple: rapid cooling, nonwettable surfaces, low turbulence, minimal gravitational forces, closed-system sterility, and rapid removal of the cytologic components before enzymatic degradation could ensue. In an effort to make these fundamental techniques applicable to tissues other than blood, the engineering was developed in such a manner that broad versatility was permitted. As a result, a basic centrifuge system was evolved which has almost equal application to virus purification, milk stabilization, and the separation of other multiphase systems. Its performance thus far has been chiefly assayed in the blood field, owing to the central theme of the originating laboratory (*2*).

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Closed System

In the design of the apparatus, all parts that come into contact with blood or other biologic material were completely segregated from the mechanical and electric components necessary for power and control. The mechanical component, designated the "cartridge," is simple in design; it is sterilizable in an autoclave and has attached to it the collection assembly and receptacles for storage of the individual fractions. The "cartridge" can be stored indefinitely in an open area, because of a locking device which assures maintenance of "closed system" sterility (Fig. 1).

Collection of the effluent fluids and cell suspensions is accomplished by means of coaxial rings which are a part of a dynamic or centrifugal valve. Thus, effluent discharged under centrifugal force is collected in an outer annular space; the material that drains after decelerating the bowl is collected in a separate, inner, annular chamber. Adoption of this principle avoids the need for manifolds to control the flow of liquids into their respective receivers. All connections into and out of the apparatus are thus made on a stationary, collecting assembly (Fig. 2).

Three basic bowl designs are employed in the centrifuge: an inverted conical-shaped, two-compartment bowl (type I); a peripheral-feed, long-traverse bowl (type II); and an inverted, cylindrical, falling-film bowl (type III). These make possible diverse types of separation which involve the removal of cells or precipitates from a liquid medium. The three bowls also possess internal flexibility by means of a locking device in the mid-portion of the bowl. This permits the insertion of various dividing baffles without change in the outside dimensions or in the relationship of the bowl to the drive mechanism. It also permits facility of disassembly for thorough washing, resurfacing, and removal of pyrogens.

Type-I Bowl

The separation of certain cytologic components of the blood is a typical example of the use of type-I bowl (Fig. 3). Blood contains three formed elements of varying average densities—red cells (1.095), white cells (1.065), and platelets (1.032)—suspended in liquid plasma. Sedimentation (either spontaneous or accelerated by rouleaux reagents) and low-speed centrifugation have generally been used for separation of the three kinds of cells. The densities of the three cell types represent average values only. Considerable variation exists in both size and weight. As a result, no single mechanical system has ever led to a pure yield of cells. Partial purification of a single kind of cells has been achieved by repeated packing of blood in a bucket-type centrifuge with pipette removal of the layer that most closely corresponds to the desired cell population. The present device permits a continuous-flow system