Current Research in Sound*

VINCENT SALMON†, SENIOR MEMBER, IRE

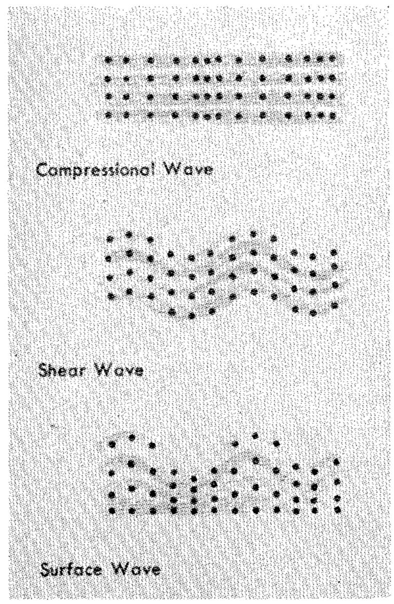
Summary—**Sounds in industry may go unheard by the ear, but they are all-important to "listening" machines, compounds, and processes. Already with sound we can test, mix, measure, clean, drill, and control. And research indicates broad new applications in the tomorrow.**

THE SKILLED MUSICIAN utilizes his talents and instruments to evoke, alter, and control the emotions of his audience. To a similar extent the well-informed production engineer can call on the resources of acoustics to measure, alter, and control the behavior of many recalcitrant industrial processes and materials. These applications of sonic energy we may class under industrial acoustics, so named out of analogy to industrial electronics.

Because industrial acoustics is as yet not a well-defined activity, estimates of its size vary. The annual dollar volume of pertinent equipment manufactured in the United States is probably in the $60–75 million range. Most of this is in sonar, underwater telephone, and fathometer devices. Equipment for other purposes accounts for scarcely $20 million, most of which is for flaw detection devices. But developments are coming so rapidly that these figures may be out of date when printed. Much of the expansion is in nonmilitary applications, especially those involving energy for industrial processing.

The worker in industrial acoustics has many sonic parameters to bring to bear on the problems brought to him. He sometimes can select the medium in which he works and its wave transmitting properties of sound velocity and absorption. More often than not, this medium is selected for him, because it is actually the workpiece to be tested or processed; and the appropriate wavelength and sound intensity range must be selected to achieve the desired effect. In a solid, functional requirements of the problem will often dictate whether the medium should be squeezed by compressional waves, rubbed by shear waves, or rippled by surface waves. In nondestructive testing and acoustic control, the information desired may lie in measurements on absorbed, reflected, bent, or scattered sound waves; often transit time, resonant frequency, and mechanical impedance are measured. The parameters are usually selected to maximize the information in an unequivocal and repeatable fashion.

In sonic processing, the desired effects usually depend on cavitation—that is, the generation of shock waves by rapidly collapsing bubbles in a liquid. The industrial acoustics engineer has all these major sonic parameters at his command and is also alert to the results from pure research that he may add to his acoustic armamentarium.



Types of sound waves in solids.

Testing with Sound

Sonic testing may be destructive or nondestructive. The necessity for the destructive testing arose in part from damage to early jet aircraft caused by intense noise from improperly located engines. This noise can also cause mal- or nonfunction of electronic gear. The test problem is to recreate jet noise of the desired intensity and frequency range without a jet engine. At present, sirens and modulated airstream loudspeakers (a mechanical version of human voice production) are employed, but neither is completely satisfactory. What is needed is a device with the efficiency of a siren and the ability of a modulated airstream loudspeaker to deliver several frequencies simultaneously.

The present research attack entails giving each device some of the characteristics of the other. An intriguing possibility lies in using the fact that a vacuum tube amplifier is in many ways analogous to a modulated airstream loudspeaker. This analogy suggests the use of the

* Received by the PGA, January 30, 1961. Reprinted from the *Stanford Res. Inst. J.*, vol. 4, 1st Quart., 1960. This is the second in a series of articles reviewing current research in acoustics and audio. The first article, entitled "Current research in communication acoustics," appeared in IRE TRANSACTIONS ON AUDIO, vol. AU-9, pp. 37–40; March–April, 1961.

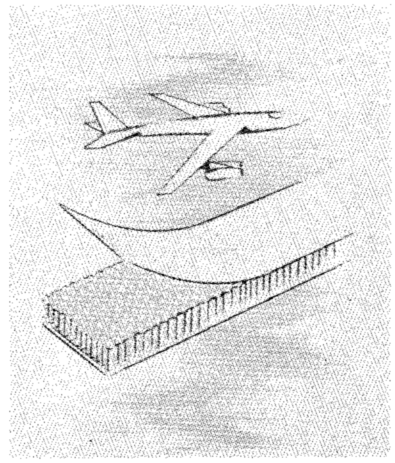
† Stanford Research Institute, Menlo Park, Calif.

positive portion of an acoustic wave to control the blowing of air through one modulator and the negative portion to control air sucked into another modulator. Thus, the total acoustic wave is synthesized by assembling the positive and negative portions. The realization of this blow-suck modulator depends on improvements in our knowledge of still intractable flow equations. Perhaps the next decade will see this roadblock removed or at least reduced to a minor obstacle.

Nondestructive testing is concerned with uncovering such properties as the strength of adhesive or welded bonds, viscosity, elastic constants, or grain size. The major application is the location of flaws in solids. Here, the principal sonic parameter is wavelength, for when the wavelength is much larger than the flaw, the wave is unaware of the presence of the flaw. For the flaws of industrial interest (in metal parts), this usually means that ultrasonic frequencies are necessary. For example, to delineate defects larger than $\frac{1}{8}$-inch extent in steel, the frequency of the probe wave should be over one megacycle per second (one million cps). Ordinarily, compressional pulses of the sound are transmitted, and the instrument "listens" for reflections from defects. The time of transit to and from the defect locates it. Many such devices are on the market, but they are hard pressed when the flaw is close to the source of the ultrasonic pulse. In this case, the echo may return while the transmitted pulse is still continuing and thus may be hidden in the transmitted pulse. At present pulse-echo devices using some species of surface wave appear fairly promising in the inspection of near-surface flaws. The precise type of wave used depends on whether the flaw is laminar (parallel to the surface) or a crack (perpendicular to the surface). Operating difficulties remain, and we shall have to rely on further research for an answer.

Glued Aircraft

The appearance of high-strength organic adhesives has made possible aircraft (such as the B-58) that are almost entirely "glued" together. Nondestructive, nondamaging inspection of such bonds in both manufacturing and maintenance involves a technique using mechanical impedance. (This quantity is the ratio of vibratory force to vibratory velocity, and plays the same part in vibration and sound that electrical impedance plays in its field.) If we vibrate an adhesively-bonded skin, its mechanical impedance depends on the quality of the bond, and several means are available for displaying this dependence. In addition to exposing a flaw, in many instances the instrument readings show good correlation with the actual bond strength, determined destructively on a statistically significant number of calibration samples. The technique has applications to welding inspection and possibly to determining the temper or anneal in glass and metal.



Much structure in supersonic aircraft is made from a honeycombed metal "sandwich," *i.e.*, the aircraft is "glued" together. The bonds of the structure can be tested nondestructively with sonic instruments.

Other Nondestructive Tests

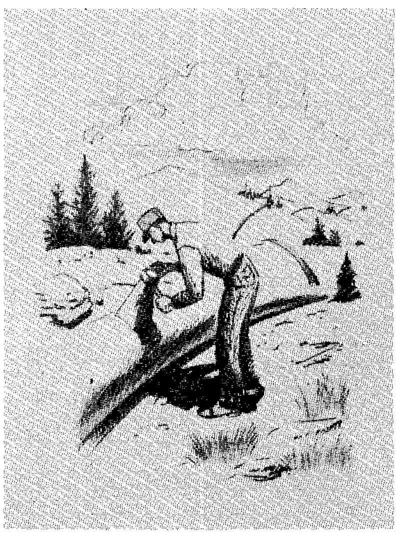
The elasticity of a material depends on both the constitution of its structural elements and how these elements are assembled. For example, in a polymer, both the elastic properties of each molecule and the degree of crosslinking between molecules control the overall elastic properties. Usually these properties must be described in terms of energy storage and energy loss, under the general heading of viscoelastic behavior. These properties can be measured with sound. Such tests are commonplace in the elastomer and textile industries, and often serve in production control as well as in product development. The extension of similar sonic testing techniques to problems in ceramics, glass and metals technology is but a matter of time. Even our present limited probing in space flight environments has exposed some severe problems. Radiation found in space can markedly alter the internal structure of materials. These effects can be simulated in the laboratory where sonic testing may be used to measure the degree of alteration.

An important example of nondestructive testing is the location of sizable foreign objects in a large body of liquid, as a lurking submarine. We know this technology better as sonar, but in principle it utilizes much the same equipment as that used in the laboratory for pulse-echo ultrasonic defectoscopy. However, the defect may now be tens and even hundreds of feet long, and the distances may be in miles. Instead of a stable and excellently-conducting medium, we have to deal with a restless, changing ocean that shatters sound beams, and bends and reflects them into an almost unrecognizable form. Research to overcome or circumvent these natural limitations is of prime importance in national defense. Perhaps the sense of urgency felt by many workers in sonar technology will communicate itself not only to acoustical scientists but also to researchers in the allied contributing fields of fluid dynamics, oceanography, information theory, computers, and what might be termed bathymeteorology, or "underwater weather study." The sonar scientist needs all the interdisciplinary help he can get.

Almost everyone has run into situations for which nondestructive tests would have prevented dangerous or unpleasant results. The ripe egg in the frying pan, the fermenting canned fruit, the windshield that dissolves at the first pebble strike, the knothole that may appear when plywood is cut, the welded Liberty ship that cracks in two—all of these involve defects that may possibly be located by sonic testing. Laboratories engaged in such research can be sure of one thing—there is no dearth of problems.

Measuring with Sound

Sound has been successfully applied to the measurement of liquid flow in pipelines, using the fact that the motion of the medium changes the apparent sound wave velocity. Still, there does not exist a general-purpose portable, sonic flowmeter that can quickly be clamped on a pipeline. The chief difficulties lie in turbulent flow in the pipe and transmission of signals in the walls of the pipe, rather than in the liquid. The researcher who first develops an easily-applied, portable, sonic flowmeter will meet an enthusiastic reception from the chemical and petroleum industries.



A portable sonic flowmeter that can be clamped on a pipeline is a research goal.

The Doppler effect is used to measure the velocity of a moving surface. This is the change of apparent pitch of a rapidly moving sound source that passes us, such as the drop in pitch we hear in the whistle of an approaching train as it comes alongside us. If a beam of sound is directed at a moving surface, then the reflected sound returns altered in pitch. Thus, the velocity of the surface can be detected without touching it. Traffic police radar does this with radio waves that reach farther than possible with ordinary sound.

With a modified sonic instrument, the spacing between fixed and movable objects may be measured. Such devices should have all sorts of application where dial or feeler gages are now used; for example, the eccentricity of rotating parts can easily be measured. Or a sonic altimeter could help helicopters land or maintain a fixed altitude above, say, a heaving sea. A similar device, horizontally directed, in automobiles would serve to indicate the distance of the car ahead in heavy traffic or dense fog.

Chemical Processing Methods

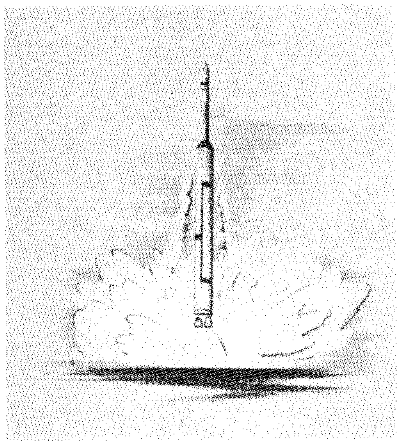
Much of sonic processing involves working in a liquid medium with sound intense enough to produce cavitation. As explained, this action results in the repeated production of intense short-range shock waves, which in turn are responsible for many of the effects observed. Cavitating sound can cause chemical reactions to begin or to proceed faster. Thus, controlled chemical attack on hard metals, known as chemical milling, can be speeded. Indeed, with proper direction of the sound beam, the chemical attack may possibly be made more selective and controllable.

In electrolysis, sonic energy can promote more uniform dissolution of the anode, and can alter the character of the deposit. Many of the effects are specific to the particular electrolyte, anode, and cathode employed and results have often not been what was desired. Ordinarily, sonic energy is regarded as another additive to the bath, when, in reality, it affects the electrode processes so profoundly that the optimum bath and current density may differ with and without sonic activation. Moreover, all too frequently sonic devices have been evaluated by immersing a sound source of unknown characteristics and output, with no quantitative evaluation. Only careful quantitative research can supply data on which engineering and economic decisions can be based.

Intense cavitation can rip apart long molecules. Thus, enzymes can be deactivated, and liquids having a large range of high molecular weights can be reduced to smaller molecular weights. This has primary application in finishes such as lacquers and varnishes, where the film-forming properties are improved by molecular weight control. However, no large-scale exploitation of this application of sonic processing has been tried yet, probably because of the high cost of the sonic energy.

An interesting application occurs in the extraction of fat from bone meal in the manufacture of glue and gelatin. Ordinarily, hot solvent extraction is used, but the extraction is incomplete, and the end product may be degraded by heat. Cavitating sound has been found to effect more complete separations at temperatures low enough so that the fat is unharmed. But the cost of sonic energy generated by conventional means is so great that it is infeasible.

One important chemical effect lies in the apparent ability of intense sound to control combustion. The glamorous example of the moment is the increase in burning rate occurring in solid-fuel rocket motors where intense self-generated oscillations can build up, sometimes until the motor is destroyed. With controlled use of this effect, we may be better able to direct rockets or to obtain more energy from oil burner flames. Research is barely getting under way, and 1961 may see the first concrete results. A major difficulty is the choice of the means of sound generation; sirens, whistles, and modulated airstream loudspeakers have been suggested.



Intense sound can control combustion, thus, perhaps, leading to more efficient rockets.

Physical Processing Methods

Physical effects of cavitating sonic energy are best typified by the many sonic cleaners on the market. In these cleaners, tiny, intense shock waves caused by cavitation literally blast the soil off the surfaces to be cleaned. Sonic cleaners provide expensive energy, and hence are most feasible where the piece part cost is high. Ball bearings, instrument bearings, gyros, hypodermic needles, and shaver heads are typical examples. Effective application of sonic energy to home dishwashers and the like does not now appear promising.

Watch cleaning is a good example in which sonic cleaners will probably supersede others. The watch may be cleaned, without disassembly, much more thoroughly than by conventional means. The decreased handling also means less chance of damaging the delicate works.

The sonic cleaner industry is gradually divesting itself of the emphasis on ultrasonic energy, for better effects are often obtained at audible frequencies. A major unsolved problem is how to specify cleaning efficiency or even intensity of cavitation. At present we do not even know what questions to ask, much less the answers. But the problem has been recognized.

Cavitation has been used in a demonstration of the emulsification of mercury and water, a laboratory curio only. Cavitation-induced shock waves shatter the mercury into very fine droplets that remain suspended for a relatively long time. Ordinarily, the energy costs too much for such mundane tasks as homogenizing milk or making mayonnaise. Probably sonically-produced emulsions will always be a laboratory accomplishment, and industrial applications will be only for the really difficult tasks.

A physical effect of cavitation that is of industrial importance is the increased transfer of heat through a liquid-solid interface. The sound produces an intense stirring action that is concentrated at the interface, and the heat transfer rate may be increased by 200 to 300 per cent. There is potential application to heat transfer in nuclear reactors, where the local heating problem on fuel elements is still incompletely solved. However, large amounts of sound are needed, and as yet we do not have inexpensive sources.

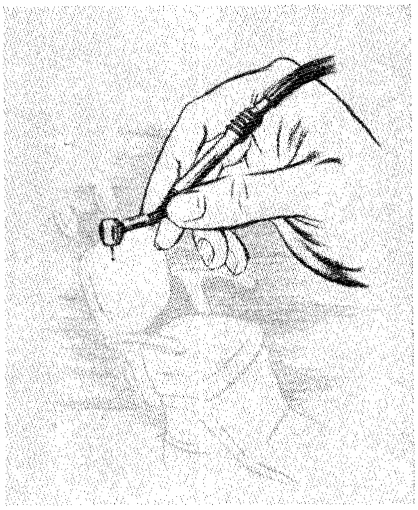
Uses with Metals

In metals technology, the use of intense sonic energy during the solidification of a metal from its melt will prevent the coarse, tree-like structures called dendrites. The final metal grains are small, and more of the resulting casting is sound. A Czech firm is rumored to have a sonic casting process in operation; it should be particularly useful in casting turbine buckets and other high-cost, high-performance parts. Isolation of the sound source from the heat of the melt is perhaps the largest problem. However, there is really no research uncertainty, and only straightforward engineering is needed to make the process practical for small, expensive parts.

Action of sound waves is greatest at the corners of a solid object when it is immersed in a liquid. This fact is being used in sonic deburring of cast or machined parts. The parts are immersed in a stirred abrasive slurry supplied with cavitating sound. Edges are speedily removed, with minimum change of critical dimensions. There should be all sorts of applications of this idea, which at present is restricted to small expensive parts because of cost.

Sonic impact grinding involves the vibratory motion of a tool to drive abrasive diamond chips against a hard, brittle material. Thus, die cavities can be sunk in very hard metals, or glass can be cut in intricate designs. Use of sonic impact grinding is now firmly established, and efforts have been made to apply it to dental drills. The misnomer, "drilling with sound," has led to some disappointment, for the drilling is done by the abrasive, which must be continuously fed in and removed from the mouth. Also, there is an unresolved controversy as to whether or not the repeated impacts will damage tooth pulp and nerve tissue. The most that can be said is that good, objective, quantitative evidence for one view or the other is still needed.

In forming metal in a die, considerable wear of the die walls occurs. It has been proposed to vibrate the walls of the die so that the metal will flow more easily, as does flour in a vibrating chute. The idea has not received a fully definitive test, but it seems likely that some useful effects should be obtained.



Sound has recently been tried as an aid in abrasive drilling in dentistry. Results are inconclusive without further objective study.

Textiles, Food, and Bugs

In textile production, one of the most fabulous fibers is the product of the oriental plant, ramie. Its stout fiber produces such long wearing cloth that even the Man in the White Suit would raise his eyebrows. Socks lasting 20 years have been claimed, though the proof is rather tenuous. Production of the ramie fibers is hampered by their affinity for the other portions of the plant. Ordinarily, retting (exposing the plant to the action of the elements) is used to separate fibers from the other plant material. However, the treatment weakens the fiber. It would seem that cavitation attack, in combination with chemical treatment, might hasten the process without undue damage to the fiber. At present there is no economic necessity for this material, so the idea has had no full and careful investigation.

Cavitating sound increases the flow of liquids through semi-permeable membranes. Thus, intense sonic energy might well decrease dramatically the time required for tanning leather. Again, the optimum tanning substance would not necessarily be the same as those used in the conventional process.

In food technology and pharmaceuticals, sonic processing has already been used on a small scale. Below the cavitation threshold, sonic agitation has increased the rate of bacteria growth by a factor of 50. However, above the threshold, the cell walls are ruptured, killing the microorganisms (or human cells) in the treatment zone.

It has already been mentioned that cavitating sound may inactivate enzymes. This could be of importance in problems involving the discoloration of foods by enzymic action.

Zoological acoustics indicates that many insects are quite sensitive to sounds in particular frequency ranges, some ultrasonic. Thus, if we know the sensitive range, it should be possible to create an exodus of small, crawling insects from foods. Then you may eat your brussels sprouts without fear of ingesting unwelcome protein. Or weevils might be chased from stored grain. Of course, the primary knowledge must come from insect studies; promiscuous use of sound on foodstuffs just to see what will happen would be a waste of money.

Source Needed

In all the foregoing processing applications of sonic energy, a large obstacle to their full exploitation is the absence of a suitable, economical sonic source. Such a source should yield high power with good efficiency, should have low installed and operating cost, should be able to be serviced by a plant plumber and electrician, and should be suitable for flow processing. No present sonic generator satisfies all these requirements.

The need for a cheap high-power device has prompted an examination of the difficulty of producing cavitation as a function of frequency. In water, below a frequency of 10,000 cps, a relatively constant amount of energy suffices, whereas above this frequency the energy requirement increases sharply. Working below 10,000 cps loses the magic appeal of ultrasonics, but gains the use of rotating machinery to produce the energy. Compact, 30 kw 10,000 cps motor-generators are readily available. Such a power source should be more attractive than a vacuum tube supply.

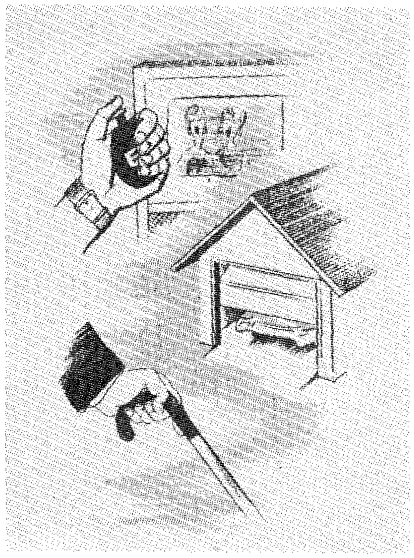
Another possible improvement in means of producing intense sonic energy is the replacement of magnetostrictive and ferro-electric (ceramic) devices by purely mechanical ones. A possible high-power source now being developed employs the same mechanism as a water valve that screams; it uses a motor, a pump, and a special valve. Called a hydrodynamic oscillator, it may well make possible a host of applications that await such a simple source.

For operation at frequencies below 1000 cps, unbalanced rotating mass force generators are available. Some are capable of acoustic outputs in excess of 100 hp when properly coupled to the liquid. Finally, in a fluid modulator, the steady stream of liquid from a pump can be changed into a pulsatory flow; this energy can readily be piped to the point of use. All these ideas are being investigated now, and should one turn out to be the answer, sonic processing should become a standard tool for industry.

Sonic Control

The use of sound waves for control involves an instrument's sensing a change and acting on it. Here we shall briefly mention a few. A popular TV remote control uses struck bars to produce ultrasonic control signals. A garage door opener employs an ultrasonic whistle operated from the car's intake manifold. Guide canes for the blind use reflections of short-wavelength sound to locate obstacles such as curbs. And an inaudible burglar alarm uses criss-crossing sound waves that detect any motion in their field. This device also detects flames and mice; the latter sensitivity had to be thwarted by a "mouse recognition" circuit. Finally, a system of sonar beacons has been suggested to replace lighthouses and foghorns. All of these control uses of sound are relatively straightforward, and need more ingenuity than research.

A phenomenon noted in all branches of industrial acoustics has been the reduction in time lag between obtaining fundamental results and applying them to the solution of industrial problems. Because fundamental research furnishes our scientific capital, we must take care that we keep it working—with a sufficient amount of its profits returned for generating more capital.



TV remote control devices, automatic garage doors, canes for the blind, are some of the many new ways to use sonic energy.