Experimental Ultrasonics

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Part II—A description of some of the problems of instrumentation for experimental work in the realm of ultrasonic frequencies.

About the minimum amount of equipment required in the investigation of ultrasonics is a source of ultrasonic power, such as the Hartmann generator, a microphone or pick-up, and an indicating device such as a receiver or oscilloscope. Of course, other indicators can be used, such as pigeons or insects, which have positive reactions of various kinds to certain frequencies and amplitudes, but the lack of some measurement devices is rather a handicap.

One great difficulty in attempting to turn out a standard line of ultrasonic apparatus is the very complexity of the requirements. A biologist might wish to investigate the effect of ultrasonic stimulation on cancer, and a cathode-ray tube production man may wish to use the well-known dust precipitation effect to more rapidly coat his screen with phosphorus. In these cases both the generators and observation instrumentation would be quite different. Also, the biologist would be rather unskilled in using apparatus of this nature.

In this article we shall discuss some design features of rather small pick-up devices, such as would be used in a probe. It is almost universally true that all these receiving probes can just as well be used as low-power transmitters, so it would be a great advantage always to design them for both functions. It is also desirable to make them immersion-proof, if possible, so they can be used in liquids as well as air or other gases. Most of them have a natural temperature limitation of some kind, also, and we wish to extend this to its highest limit possible.

Another requirement is small size. These are to be used in sonic fields of small wave-length, and in general we wish them to disturb the field as little as possible. Of course, if we work up around the megacycle region, the physical size must be many wavelengths in dimension for practical apparatus for general use, although special microscopic devices can be made if the requirement justifies the expenditure.

Test chamber used with two transducers for experiments with transmission through various media. One of the transducers of Fig. 1 is shown separately.

Shielding against powerful electromagnetic or electrostatic fields is often necessary. As a rule, 60-cycle hum pickup is small, but can be troublesome if not kept in mind. A particularly difficult case is when two magnetostrictive probes are used close together as transmitter and receiver. Very often the flux leakage from the transmitter will directly excite the receiving unit and the supersonic coupling through the medium will be masked.

It is a great advantage to design a series of units interconnected with modern, 52-ohm concentric cable. It has a nice line of fittings available for all purposes, provides good shielding, is low-loss at all frequencies we may wish to use, and is very neat and durable. Unfortunately, about the only type unit that can readily be made to match this low impedance is a magnetostrictive one. All the piezoelectrics suffer severely from the high capacitance, and sometimes it is necessary to go to troublesome or expensive steps to overcome this.

A real hardship in designing a line of units is the wide frequency range we generally wish to cover in general experimentation. A final commercial installation can often be designed to operate at one frequency only. Before we can determine this optimum frequency it may be necessary to investigate an enormous range of many octaves. In working with small particles in water it is usually interesting to investigate the entire spectrum from 10 kc to nearly 10 mc. This is a real test of the designer.

It is the purpose of this table to give a rather rough idea of the frequency limits of various transducers we may wish to use. The range designated as "natural" shows the frequency limits within which no unusual difficulty is had in normal design. The "extreme" range shows maximum performance ever observed by several experimenters. It may be only a single sharp peak shown in some unusual mode of oscillation.

Significance of the Resonant Peak

In general terms, we can operate our devices at resonance or off resonance by any desired amount. Since

TABLE 1

Device	Natural Range	Unloaded Q	Extreme Range	Max. Temp. (F)
Rochelle Bimorph	0 to 30 kc		0-2 mc	120
Rochelle single	0 to 300 kc	20,000	0-3 mc	120
PN	0- 200 (piston)		0-3 mc	250
Magnetostriction	10- 100 kc	30,000	200 kc	250
Rubber electrostatic	10- 500 kc		3 mc	150
Quartz	50- 7,000 kc	10,000	Very high	1,000

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many show unloaded Q values that are very high, we can mount them so that high Q is maintained, or load them down to almost any extent.

The chief argument for high Q is the great output obtained at that resonant peak, a very strong argument indeed. The price one pays for it is high, however.

If the units are operated in pairs, one being the loudspeaker and the other the microphone, this resonance rise is squared, and the output is very favorable. The frequency stability on the transmitting signal source must be very great indeed, and in general is hardly practical. If we use a precision frequency standard for the signal to drive the transmitting transducer, it will not follow the transducer peak in many cases, as the transducer is out on the firing line, subjected to variations in temperature, vibration, pressure changes and the like while the standard crystal is locked up in a temperature oven. Also, in the field standing waves with ratios of ten to a hundred are rather common, and these change due to local conditions.

This severely limits the use of the high-Q transducer. So in practice a load sufficient to bring the Q down to as low as ten or thereabouts is often employed. Even at this low Q standing waves are severe, and frequency modulation must be employed to break them up.

This loading does not seriously affect the off-frequency operation of the devices, but of course operation off frequency severely cuts down the signal. A typical example is a pair of one-quarter inch cubes of PN crystal suitable for stable operation in a water supply which might have particles in it. At 200 kc operation, resonance for both units, an input of 200 volts of signal on one will give perhaps 2 volts on the receiving crystal, while off resonance at say 150 kc the combination might give an output of 5 millivolts or so.

Diaphragm Design

The only transducer diaphragm easy to design is the magnetostriction type. It is inherently rugged and needs little protection from gas or liquids. A simple metal disk silver-soldered on the end of the nickel rod, gives almost any desired acoustic impedance match.

PN and Rochelle crystals are very fragile and must be protected from shock and damage if used as contact microphones. PN instantly melts if one drop of water comes in contact with it, but Rochelle salt often can be given a protective coating to prevent this. Quartz has high resistance and moisture must be kept out to preserve the insulation of the assembly. A 7-mc quartz crystal, of the X-cut type is about 20 mils thick, and is quite fragile.

So we have our choice of rubber (plastic) diaphragms, or solid metal. The rubber must be quite thin and offers little protection from sharp points. However, diaphragms made from thin rubber, nylon, or Teflon of a thickness of only two mils or so are very easy to handle, as below 200 kc or so they have little effect on the transmission of ultrasonics through them. To provide clean-cut effects, they must be placed under tension in some way, and the mounting made waterproof by some means.

Standardized Shell For All Frequencies

Figure 1 and the photograph show an earnest attempt to design a universal shell of wide application in ultrasonic commercial and experimental work. In most cases it has a metal diaphragm. This was designed to operate through the spectrum from 10 kc to 7 mc, using practically any type of transducer from magnetostriction to X-cut quartz.

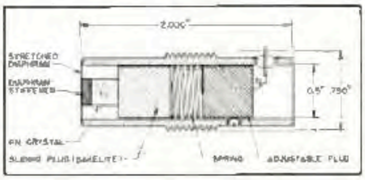

Fig. 1. Universal shell design for transducer suitable for wide range of ultrasonic frequencies.

An accurate half-inch bore dimension was used with a thick wall so that set-screws and glass-bead lead-throughs could be used. A three-quarter inch thread was formed on the center section and this made the tube outside diameter 0.690 inch, as this cleared the root diameter of the thread. This thread was made rather fine, 24 threads/inch, as very often we want fine adjustment of the position of the diaphragm in our tests. The shell was usually made of monel, because it is an attractive material unaffected by many liquids. Sometimes it was hard chrome-plated, or gold plating was called for. A length of 2 inches worked out well.

The series of diaphragms gave us the most trouble to design. If we use quartz or PN crystals, they are mechanically dead flat, and the diaphragm is often used under at least city water pressure, which might reach 60 pounds/square inch at times.

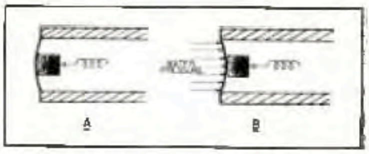

Fig. 2.(B) When used under pressure, diaphragm is pushed inward, providing contact on only a portion of the crystal surface. (A)Pressure behind the crystal bulges diaphragm outward, provides contact only on corners.

This bulges the diaphragm inwards, as shown in *Fig. 2B,* and the crystal would only touch in the center of its working face. In general, we need some pressure driving the crystal against the diaphragm, to obtain intimate contact, and with no pressure on the outside of the diaphragm a reverse bulge takes place, as in *Fig. 2A,* and the crystal touches on the corners only.

By soldering a one-quarter inch button to the center of the diaphragm, we accomplish two objectives: At some high frequency any diaphragm breaks up into complicated modes of oscillation, which produce lobes in the radiated or received pattern. A piston action is much easier to analyze and use. This local thickening in the center turns the quarter-inch center into a piston very well, as experience has shown, and gives a pattern very easy to use.

In practice, some care must be used in making and mounting this center button. Since it will often be used with a precision finished transducer element, it must be dead flat and squarely mounted. If slightly cocked, the pattern put out is hard to analyze, and results are undisciplined.

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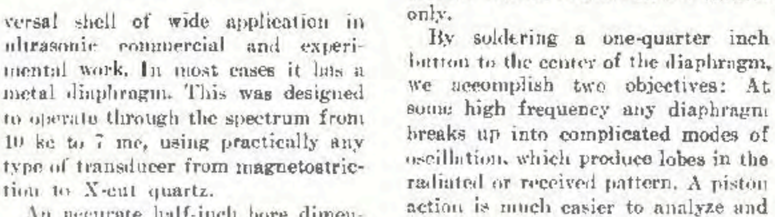
Transducer probe for use in air. Details of the interior of the crystal mounting are shown in Fig. 3.



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Stretching The Diaphragm

The diaphragm material can be nickel, monel, German silver and so on. For any reasonable predictability of results, it must be stretched. This proved rather difficult. Welding around the rim did not work out too well, as the joint was required to be waterproof under 100 lb of pressure, and welding often left small gaps. It was finally soldered in a jig that kept the diaphragm under tension during the soldering operation. A jig was constructed that could be placed in a furnace and brought to 400°. After precision tinning both the diaphragm and the shell, as well as the button, the assembly was slowly brought up to heat and a ring of solder flowed around the joint. Slow cooling gave us a stable assembly, and the diaphragm was turned off flush.

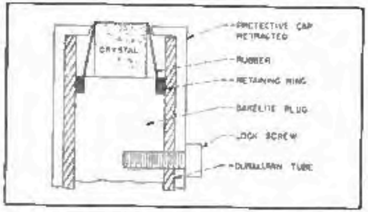

Fig. 3. Details of end of transducer probe suitable for use in air or gases.

A diaphragm thickness between 4 and 6 mils proved practicable. The button thickness did not prove critical in the sense that a thickness of a quarter or ha[illegible]ve showed up in greatly increase[illegible]tput. The thicker the button, the less the output, in general. For stiffening, a thickness of 6 mils proved adequate.

Crystal Mounting

In general, a sliding reaction type mounting was used. If we assume the diaphragm will be bulged inward by external pressure, then we attempt to spring mount the crystal so it can move longitudinally with the slow displacement of the diaphragm. This works out well if good sliding fits are made.

Loading the crystal with a lead block did little good above 50 kc or so, a small mass sliding bakelite plug being sufficient to back the crystal.

Characteristics of Various Crystals as Mounted

In general, the Rochelle bimorph of either bender or twister type, such as are used in phonograph pickups, gives great output in isolated peaked responses, with no uniformity of output at all. Its modes of oscillation above 10 kc are so complicated as to defy analysis. If you just wish to know that some supersonic energy is in the medium, the bimorph will often be a guide with occasional flashes of output up to several megacycles, but for quantitative work it is useless.

Quartz has little response off resonance, especially when we attempt to drive one quartz with another through some medium. So in general, they are useful well above a megacycle, where other devices are unusable, and then we must frequency modulate the transmitter quartz crystal for practical applications. The combination then works rather well. With a swept band of 100 kc or so at 5 mc, and 200 volts input, the receiving unit will pick up about a millivolt of signal. Quartz must also be used when the temperature is much above 250° F.

A word of warning—practically all wartime quartz was shear cut, so do not attempt to use it under penalty of extremely complicated radiation patterns, useless for any practical purpose.

Primary ammonium tartrate crystals (PN) are about the most promising. They can be used at boiling water temperature. They readily come up to an inch in length in pure piston action, cut with a natural period of about 50 kc, are fairly sensitive and have low noise level. They have too low a capacitance to be ideal. A half-inch cube has about 0.8 μμf capacitance, so they suffer from the shunt capacitance of a long lead or a vacuum tube voltmeter or oscilloscope.

Since they very readily dissolve in water, any mounting must be waterproof. Any handling with the fingers should be avoided, as they are gradually eroded by finger sweat. They are quite soft, about like a cube of sugar in hardness, so they are easily damaged by a blow, or a sharp-pointed instrument.

Another controlling difficulty in making a stable permanent mounting of the PN is the fact that no pressure can be used except on the working faces. These come marked with a little black dot, and the crystal must be wholly supported by simple direct pressure on these faces only. Otherwise its sensitivity and resonant period will be seriously and erratically affected.

The writer has used these mostly in the form of cubes. Samples are furnished to very exact dimensions, and dead square.

When mounted in the shell of *Fig. 1*, they are very stable and uniform. Care must be taken that no sharp blow on the diaphragm crushes the crystal but a reasonable amount of care will prevent this. However, the metallic diaphragm lowers the sensitivity very much when used in air or a gas, so the mounting shown in *Fig. 3* was developed.

This mounting as a probe has several advantages. The stretched rubber of a thickness of about 0.3 thousandths damps the crystal somewhat, but an absolute minimum. It has no characteristics of its own to speak of as a diaphragm. However, it does not do a very good job of protecting the crystal, and when used as a contact microphone considerable care is required not to damage the crystal. When used on the body there is little danger, but when working around metal parts that have sharp edges, great care must be used. The sliding protective metal sleeve should be only retracted when the crystal is actually in use.

When used with a high-intensity source, such as the Hartmann generator, this unit gives out a volt or two to drive an oscilloscope, if within two inches of the generator, and in the maximum field. It will give the same with the parabolic reflector ten feet away, sharply focused on the face of the crystal. However, this is only true with about two leads about two feet long and separated. If a six-foot concentric cable is used the signal drops rapidly for each foot of cable. For serious work a cathode follower stage right at the crystal and impedance matching itno the 52-ohm line is required.

Unit Used as Transmitter

Any PN crystal will take 200 volts of drive. If you wish to operate over a wide band of frequencies this offers some problems.

Suitable oscillators should cover the spectrum from ten to a few hundred kc or higher. The output must, of course, be stepped up in voltage by some means.

One means is a tuned circuit right at the crystal. Due to its very small capacitance, this is rather easy to do. Somewhat more difficult is designing a wide-band transformer to step up the 52-ohm line to match the crystal. Another answer is a driver tube at the crystal, choke-coupled to it.

A warning on using the crystal as a self-frequency determining oscillator. By the time the crystal is loaded with a diaphragm and damped by the mounting, it is seldom possible to have it develop sufficient reactance to act as a normal oscillating crystal. This is especially true if it is immersed in water, where the Q often falls to ten or less. The writer made a determined but unsuccessful effort to lock such a crystal to an unstable oscillator.

Working Units in Pairs

Two similar units work well in either air or water. For a first experiment, have them face to face and join them with a drop of water. The signal transmission will be very good.

If they are used with only air in between, very high values of standing-wave ratios will be noted as they are moved apart. These may be 40 db or so. These are obtained only when they are dead parallel and dead concentric on the same axis.

If used in a test chamber, as shown in photograph, some interesting effects can be observed. If we gradually fill the chamber with water, reflection from the underside of the water will be almost 100% and wave cancellation will occur, and by careful filling drop by drop a range of signals of 60 db or more will be had. This means that a test cell such as this must be a complete housing with no water surface on top. So the filling orifice must be closed by a plug whose inner wall is flush with the inner wall of the tube. With a suitable selective receiver, almost any of these units will pick up the ticking of a watch up to 200 kc or so, even through several hundred feet of wire. Some interesting work might be done on machinery noise, especially high-speed machinery. Most of the analyzing now done acoustically cuts off at rather low frequencies.

It is somewhat of a shock to find that the ordinary telephone receiver, when overloaded by loud speech, gives out detectable energy up to 100 kc at least. We might investigate direct pickup of noise above 20 kc from a phonograph needle tip. The noise spectrum direct from a grinding wheel may tell us how many of the cutting particles are engaging the work, and might be used as a feed control. We know it will be difficult for a reader of AUDIO ENGINEERING to locate a cockroach to chivvy with ultrasonics, but if he is given his dinner on the diaphragm of one of these units the noises are very unusual.

In the next article of this series we will discuss the design of suitable receivers, tuned voltmeters, and the like. It is obvious to select a communications type receiver for frequencies above 550 kc or so, but many of them are too sharply selective for some uses. The range from 10 kc to 550 kc requires very special design indeed.