The Supersonic Reflectoscope, an Instrument for Inspecting the Interior of Solid Parts by Means of Sound Waves

FLOYD A. FIRESTONE*
Departments of Physics and Engineering Research, University of Michigan, Ann Arbor, Michigan
(Received August 6, 1945)

THE supersonic reflectoscope is an instrument for the measurement or non-destructive testing of solid parts for flaws, by sending supersonic sound waves into the part and observing reflections from the boundaries of the part or from flaws within it. The reflectoscope has been developed at the University of Michigan in a research program which has continued for several years.

Figure 1 illustrates the principle of the reflectoscope as applied to the inspection of a block of metal. A quartz crystal makes effective contact with the work through a thin film of oil which is squirted onto the surface of the work. The upper and lower faces of the crystal are provided with conductive coatings and the crystal has the property that when an oscillatory voltage is applied between these coatings the crystal grows thicker and thinner in synchronism with the electrical oscillations. This causes the lower face of the crystal to vibrate and thereby radiate sound waves through the oil film into the work. By proper choice of the thickness of the crystal, it will give a thickness resonance and correspondingly increase the strength of the sound waves radiated. The sound waves are not radiated continuously but only for a short time interval; typical operation would consist in applying 500 volts to the crystal at a frequency of 5 mc (5 million cycles per second) for 1 microsecond (1 millionth of a second). Thus a group of only 5 waves is radiated, the wave-

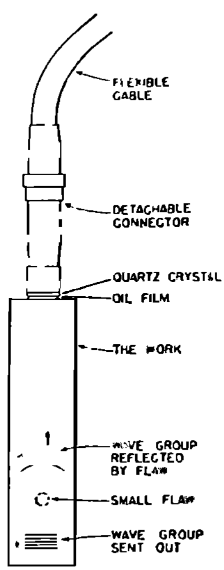

FIG. 1. Principle of the supersonic reflectoscope. A quartz crystal making contact with the work through a thin film of oil sends into the work a wave group consisting of just a few sound waves of short wave-length. This wave group is reflected from the side of the work most distant from the crystal, and upon striking the crystal generates in it a voltage whose time of arrival is indicated on a cathode-ray oscilloscope. The flaw is detected by the fact that it reflects a part of the wave group back to the crystal and this reflection arrives at the crystal *before* the reflection from the distant side of the work.

FIG. 2a. Type A supersonic reflectoscope.

* Consultant to Sperry Products, Inc., Hoboken, New Jersey.

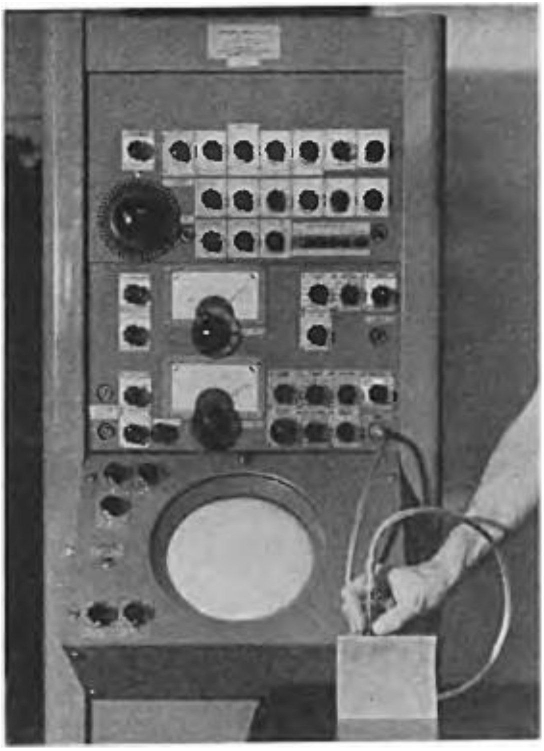

FIG. 2b. Closeup of the panel of the Type A reflectoscope showing the 9-inch diameter oscilloscope screen. The crystal is being held against a block under test.

FIG. 2c. Fixed focus camera which is quickly attached for recording reflectograms when desired, although visual observation of the oscilloscope screen is the usual practice.

length in steel or aluminum at this frequency being approximately .050″ and the total length of the wave group .250″. If the crystal is 0.5″ square, the waves will be radiated in a beam, like a searchlight beam, whose cross section is 0.5″ square. Since the velocity of longitudinal sound waves in steel or aluminum is approximately 250,000 inches/sec., the waves travel one inch in 4 microseconds, and if the block shown in Fig. 1 has a vertical dimension of 4″, the wave group will be approaching the bottom of the piece as shown about 15 microseconds after having left the crystal. This wave group will be reflected from the bottom face of the work and will get back to the crystal 32 microseconds after having been sent out. The quartz crystal also has the property that when it is subjected to the oscillatory pressure caused by the impingement of the sound waves against its face, it generates a small voltage between its coatings, which in the present example might be of the order of magnitude of .05 volt. This small voltage is amplified

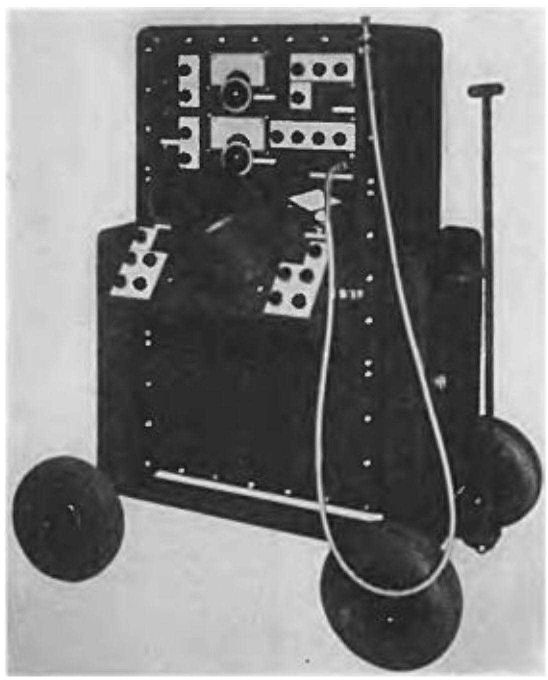

FIG. 3. Type B Sperry reflectoscope.

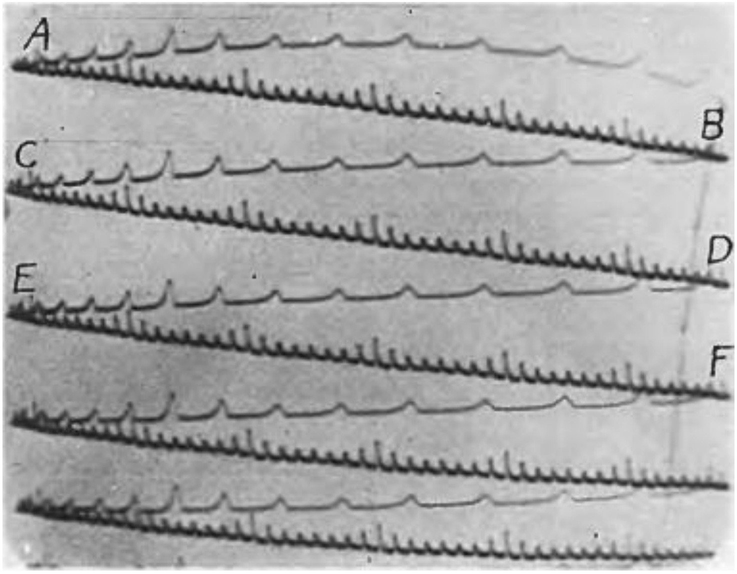

FIG. 4. Type A sweeping and timing system. This is the pattern which appears on the screen when the crystal is not being energized. It consists essentially of a time scale which is formed by the green spot of the oscilloscope traveling along the zigzag path *A*, *B*, *C*, *D*, etc. Each microsecond the spot is deflected slightly upward so as to notch the line and thereby form a timing scale. Every eighth notch is made higher in order to assist in counting. There are eight of these higher marks per zigzag so that it requires 64 microseconds to traverse one zigzag.

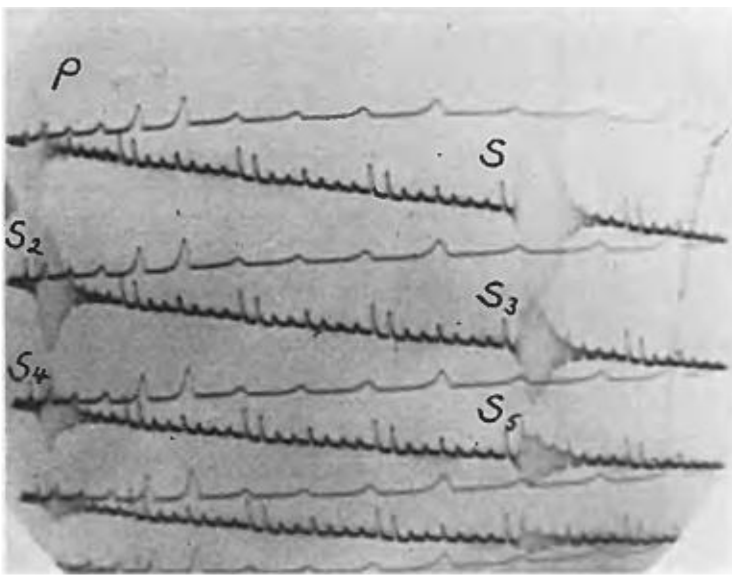

FIG. 5. Flaw detection. The crystal is now in contact with a four-inch block as shown in Figs. 1 or 2b. There is no flaw in the path of the waves under the crystal. Any oscillatory voltage across the crystal shakes the oscilloscope spot vertically and thereby widens the line. The crystal was first energized by the 500 volts for 1 microsecond when the oscilloscope spot was at *P*. This is indicated by a widening of the line. While the group of sound waves was traveling through the block and being reflected back to the crystal, the oscilloscope spot was traveling toward the right in the top line and a notch was being made each microsecond. When the waves struck the crystal the line was broadened exactly following the 32-microsecond mark. In fact, since it takes 8 microseconds for the sound wave to travel through one inch of aluminum and return, we may think of the time scale in the reflectogram as a distance scale, considering the interval between the longer marks as inches which are divided into eighths. We see therefore that the reflection at *S* begins just following the four-inch mark. When the waves strike the crystal, they do not stop but are reflected back through the block for additional round trips; and each time the waves strike the crystal, a reflection is indicated, as for instance at the 8-inch mark at S_2, the 12-inch mark at S_3, the 16-inch mark at S_4, etc. Since there are eight inches per horizontal line counting the return sweep and the block is four inches through, the successive reflections should form two vertical columns, in fact the exact time value of the time marks is adjusted until this relation holds; this constitutes a very simple procedure for adjusting the inch marks to be accurately inches, although the timing marks are then not accurately microseconds. If we were looking for a flaw, the only portion of this pattern which we would inspect would be the top line as far as the four-inch mark; since no reflection appears in that region, we know there is no flaw in that part of the block which lies under the crystal.

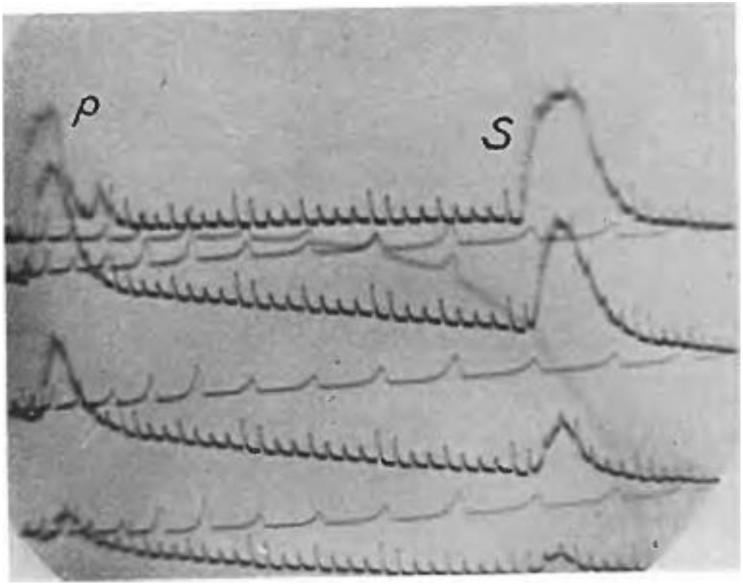

FIG. 6. Flaw detection. This is the same as Fig. 5 except that in order to improve the visibility of the reflection the spot has been deflected upward by the reflections, instead of being shaken up and down. Again no flaw. It is important to note that the entire process of energizing the crystal, sending out the waves, sweeping the oscilloscope spot, putting in time marks, and obtaining reflections, is repeated sixty times per second, so that the indications on the oscilloscope appear to the eye to be continuous, and they do not change until the crystal is moved to a new spot; each reflectogram photographed here is a 0.5-second exposure and therefore consists of the superposition of 30 tests; note the accuracy with which they overlap. By continuously moving the crystal along the work while observing the reflectogram one quickly inspects the entire interior. Compare Fig. 7.

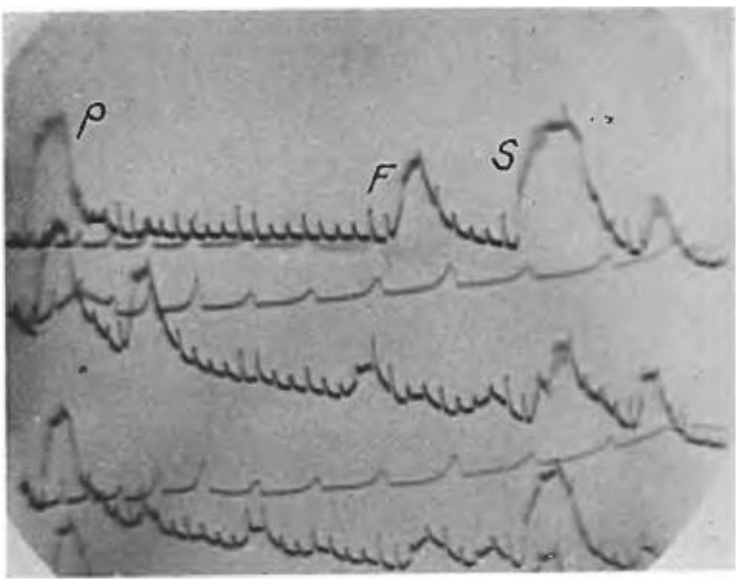

FIG. 7. Flaw detection. On the same four-inch block as Fig. 6, the crystal is now held over a test flaw three inches below the surface consisting of a hole .012″ diameter drilled into the block one quarter inch and struck by the waves broadside. The large reflection from the hole appears at *F* just following the three-inch mark and preceding the reflection *S* from the other side of the piece which just follows the four-inch mark. Much smaller flaws than this have been detected; a spherical hole .005″ diameter and about 3″ from the crystal can be detected; a spherical hole .060″ diameter five feet from the crystal can be detected, assuming that the material has a small grain size. Metal can be penetrated to a depth of the order of ten feet, the range depending on the grain size and the wave-length used. Higher frequencies and shorter wave-lengths have shorter range but will detect smaller defects. All of the reflectograms shown here were taken at a frequency of 5 mc.

and indicated on a cathode-ray oscilloscope in such a manner as to enable the time of round trip flight of the waves to be measured.

If now the block of Fig. 1 has a small flaw 3″ from the crystal as shown, a small amount of the wave energy which passes it will be reflected back toward the crystal, and will arrive at the crystal 24 microseconds after having been sent out. *Thus the presence of an interior flaw is indicated by the receipt of a reflection back at the crystal before the reflection from the other side of the piece gets back to the crystal.* By measuring the time of round trip flight of the reflection from the flaw we can determine its distance from the crystal within less than one-sixteenth of an inch, and we can locate its position laterally

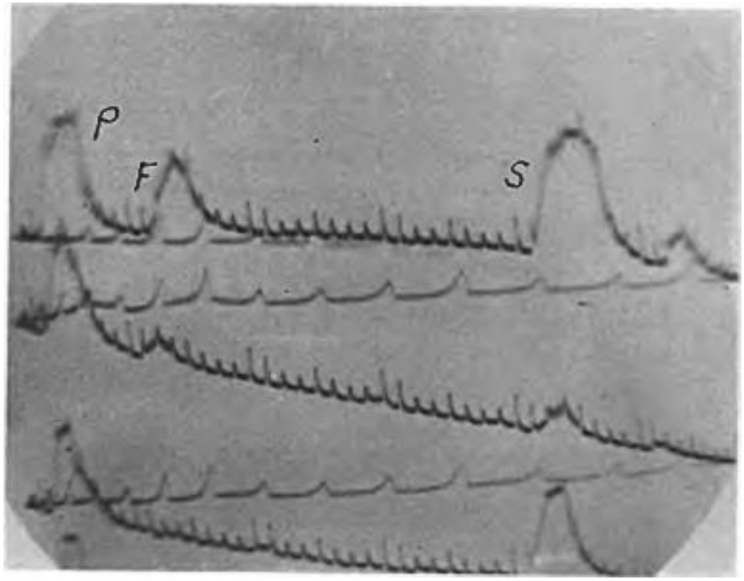

FIG. 8. Flaw detection. Same as Fig. 7 but with the block turned over so that the reflection from the test flaw is one inch from the crystal and shows at *F*.

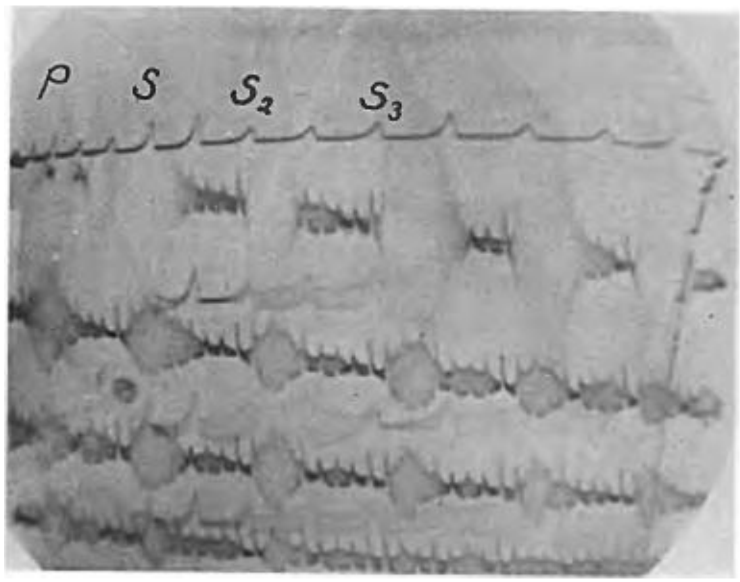

FIG. 9. Wall thickness measurement. We sometimes wish to know the wall thickness of a cored casting or of a pipe carrying corrosive material, where the inside surface is inaccessible. The crystal is placed against the wall and a series of successive reflections is obtained; the average distance between them is read off of the inch mark scale and is the thickness of the wall. Above is the series of reflections through a wall one inch thick; note that a reflection follows each one inch mark. The accuracy of this method is of the order of five percent; it depends on the smoothness, flatness, and parallelism of the wall faces.

within less than one-eighth of an inch by noting that we will get strongest reflection from the flaw when it lies on the line directly under the center of the crystal.

For convenience, the whole process of sending out the wave group and observing reflections is repeated 60 times per second so that we appear to have *continuous* indication of flaws on the oscilloscope; the crystal may be slid along the surface thereby continuously inspecting the region along the line directly beneath the crystal. The same quartz crystal is ordinarily used both for sending and receiving the waves.

There is nothing occult about "supersonic" waves in metals; the word supersonic here refers merely to the fact that the frequency of the waves is higher than audible. Supersonic sound waves are better than audible sound waves for inspecting metals because the short wave-length supersonic sounds are reflected from small flaws

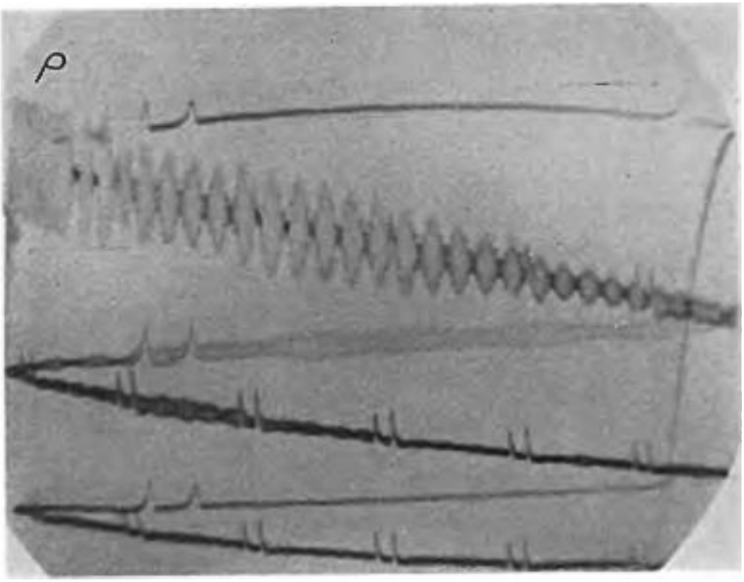

FIG. 10. Wall thickness measurement. Same as Fig. 9 but with a wall of thickness $\frac{3}{16}''$.

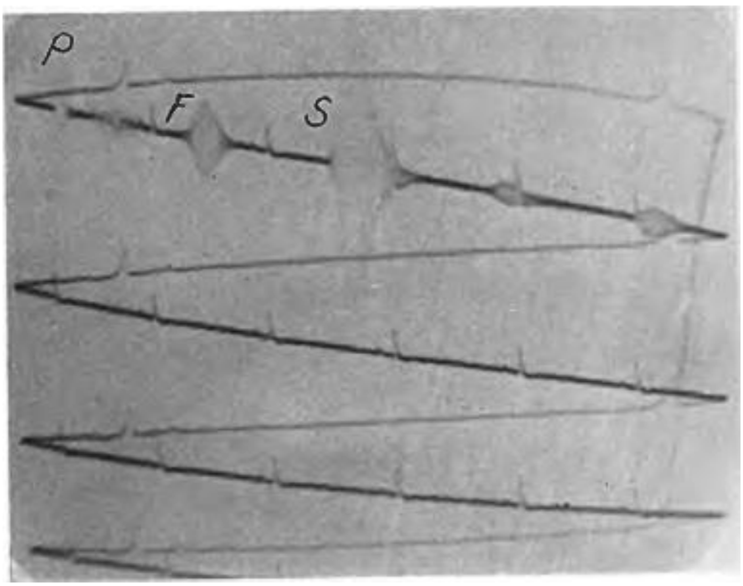

FIG. 11. Lamination detection. The crystal is placed against the side of a 2.5″ piece of rolled steel plate, the reflection from the opposite side being at *S* while there is a moderate sized flaw at *F* halfway through the plate. Compare Fig. 12.

while the long wave-length audible sounds would flow around and past the flaws without appreciable reflection. In order to get appreciable reflection from a flaw, the wave-length must not exceed the smallest lateral dimension of the flaw by too large a factor. A second useful property of short wave-length sound waves is our ability to direct them in a beam. While we are accustomed to audible sound waves in the air bending around corners, the short wave-length supersonic waves used by the reflectoscope appear to travel in straight lines like light waves, and for the same reason—their short wave-length. The longitudinal waves which the reflectoscope normally uses, travel through the interior of the metal part and the particles of metal vibrate in the line of propagation as the waves pass.

As a microsecond is not very long, being the time required for a beam of light to travel

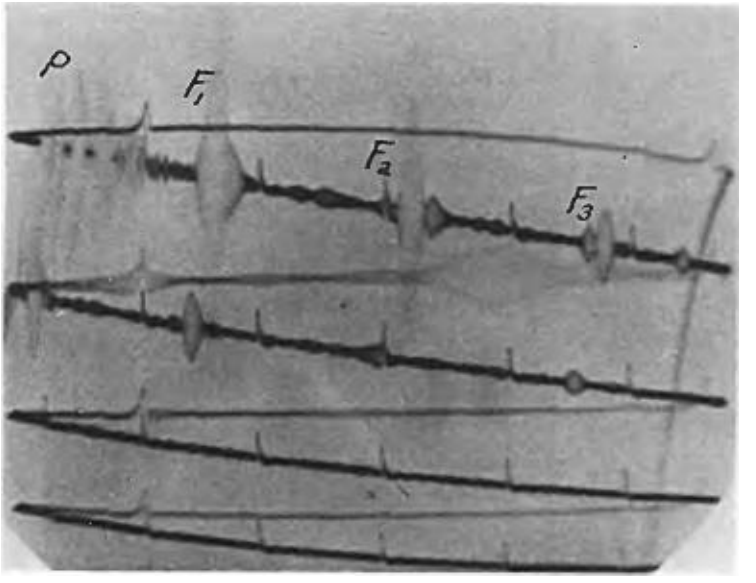

FIG. 12. Lamination detection. The crystal is now held against a different spot on the same 2.5″ rolled steel plate as Fig. 11. Here the plate has a lamination about 1.5″ from the crystal and of projected area greater than the one-half inch square of the crystal. The waves from the crystal are therefore completely reflected by the flaw and do not reach the opposite side of the plate at all. The reflections F_1, F_2, and F_3, shown above are therefore just successive reflections between the flaw and the crystal. By moving the crystal over the surface of the plate the laminated area can be accurately outlined merely by noting a change from the reflectogram of Fig. 11 to that of Fig. 12. The thickness of the lamination is of no consequence; .0001″ of separation will give as large a reflection as any greater spacing. The interface between two Johansson gauge blocks stuck together gives a good reflection (and also considerable transmission).

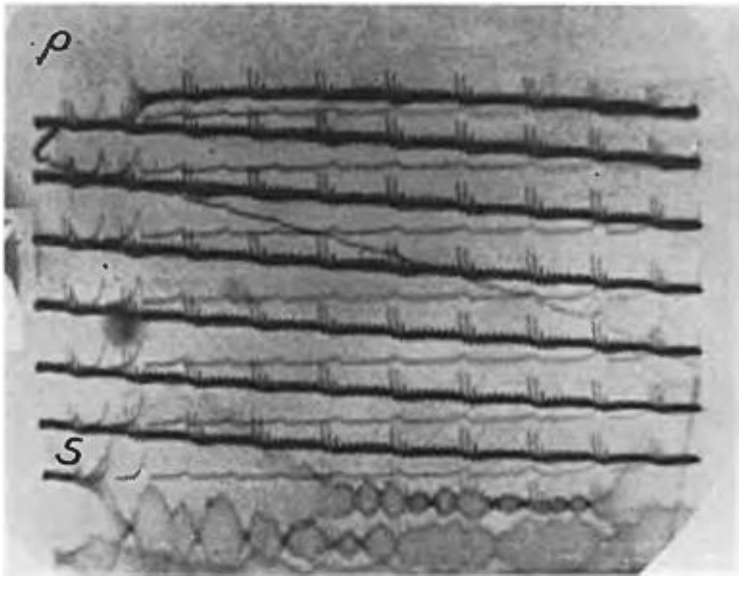

FIG. 13. Flaw detection. The crystal is held against the end of a plate one-quarter inch thick and seventy inches long. A large reflection S is obtained from the opposite end of the plate and no reflections are observed from internal flaws. Ten or twenty feet of sound metal can be penetrated if its grain size is not too large. Compare Fig. 14.

approximately 1000 feet, the apparatus for carrying out this principle in a way which will be useful in industry must be both refined and rugged. Figures 2a and 2b show the earlier Type A supersonic reflectoscope as it was developed at the University of Michigan. Although some of these Type A reflectoscopes have been used in production, they may more properly be considered as laboratory instruments, while the model for general industrial use is the Type B shown in Fig. 3, as developed and now leased by Sperry Products, Inc., Hoboken, New Jersey. Types A and B are equally sensitive, but Type A has a more detailed system of timing marks for measuring distances, although the preliminary adjustment of these timing marks requires the manipulation of the extra set of knobs shown on the upper panel of Fig. 2b. Most of the illus-

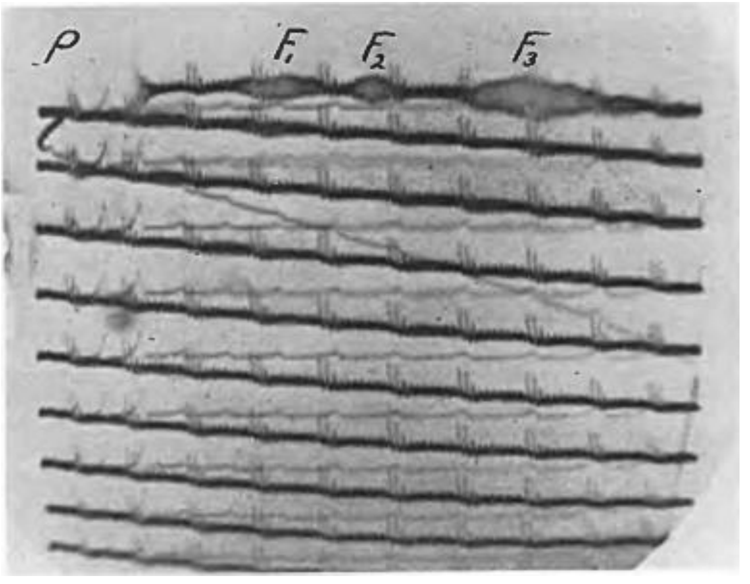

FIG. 14. A plate similar to Fig. 13, but full of small inclusions which give random reflections F and prevent any reflection from being observed from the opposite end of the plate.

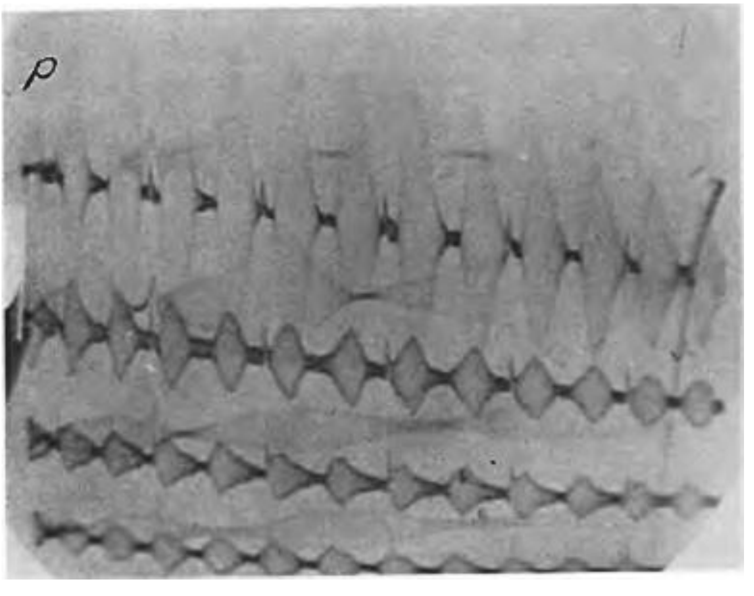

FIG. 15. Bond determination. A plate ½″ thick was built up of two plates one-quarter inch thick bonded together by an undisclosed method. The crystal being placed against one face of the plate gave a typical reflectogram as shown above showing a long series of reflections exactly ½″ apart. There was no observable reflection from the bonded interface. The plate appears to be a solid piece. Compare Fig. 16.

trative reflectograms shown in this paper were made with Type A, because these photos happened to be available at this writing, but Type B reflectograms would have been equally convincing. While Type A has a considerable number of knobs which may require adjustment when making the set-up for a new type of test, in routine operation all knobs are left fixed with the possible exception of the amplification control; thus a skilled man is required for set-up, but routine operation can be carried out by unskilled help. Type B, it is noted, has been simplified in this respect.

In Fig. 2b the crystal is shown being held against a test block, 4 inches through, such as was used for illustration in Fig. 1. Crystals of different frequencies from 0.5 mc to 12 mc may be plugged onto the end of the cable; lower frequencies and longer wave-lengths permit greater penetration of coarse grained materials

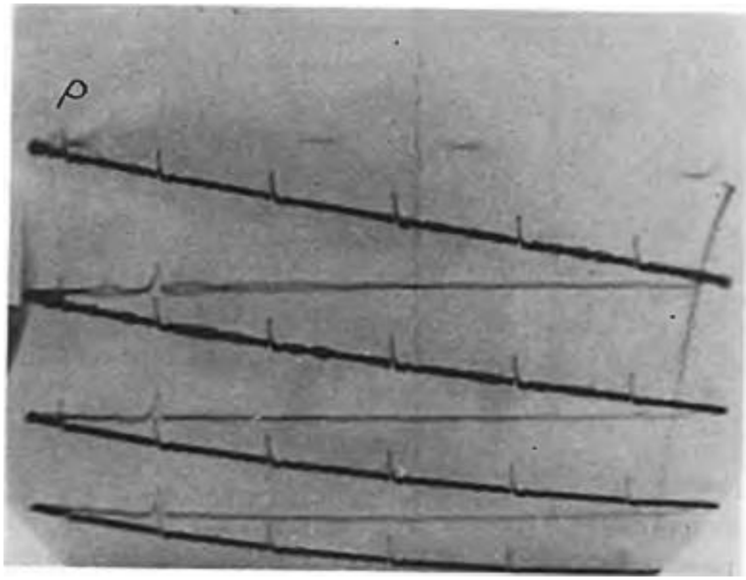

FIG. 16. Bond determination. Same plate and same conditions as in Fig. 15 but with the crystal above a spot larger than the crystal, having bad bond. In this case, the bad bond has caused the waves to be absorbed, probably caused by the presence of some flux; if the area of bad bond were clean, a series of reflections one-quarter inch apart would have been observed. In either case the area of bad bond can be easily outlined by moving the crystal.

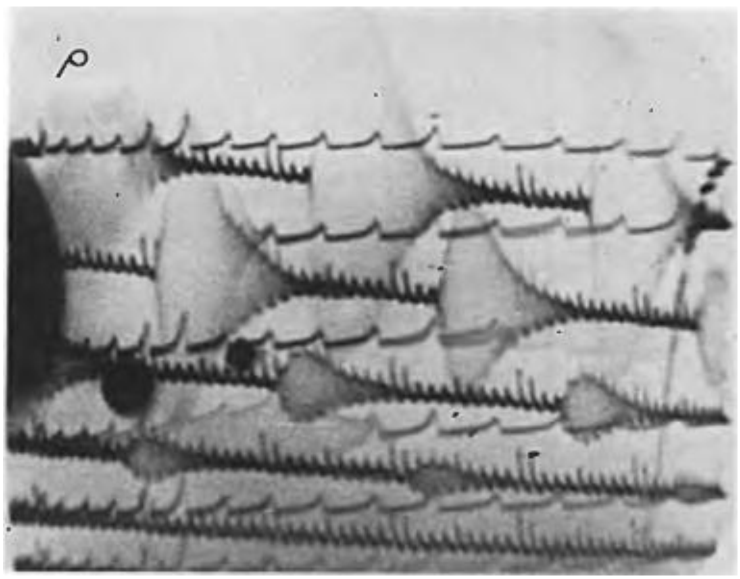

FIG. 17. Average grain size measurement. A piece of rolled brass sheet ½" thick was cut into strips 2" wide which were annealed at different temperatures. This one was annealed at 1060°F and has an average grain size of .03 mm as measured by microscope. Reflections were obtained through the 2" dimension. Note that 12 successive reflections are observable in the above reflectogram. Compare Figs. 18 and 19.

while high frequencies and short wave-lengths permit the detection of the very smallest defects. The flexible cable may be as long as ten or twenty feet at some small sacrifice of sensitivity. The various knobs on the panels are for tuning the circuit which energizes the crystal, for focusing the oscilloscope tube, controlling the oscilloscope sweep, introducing the timing marks, etc. The 9" diameter screen of the oscilloscope tube can be seen in the center of the instrument; the screen is slanted for ease of observation when working at the bench.

Although visual observation of the screen is the usual practice, when it is desired to record reflectograms, a fixed focus camera as shown in Fig. 2c may be used on a tripod which can be attached in a few seconds and it was with such a camera that the reflectograms shown in the remainder of this paper were obtained. The detailed principle of operation and a number of

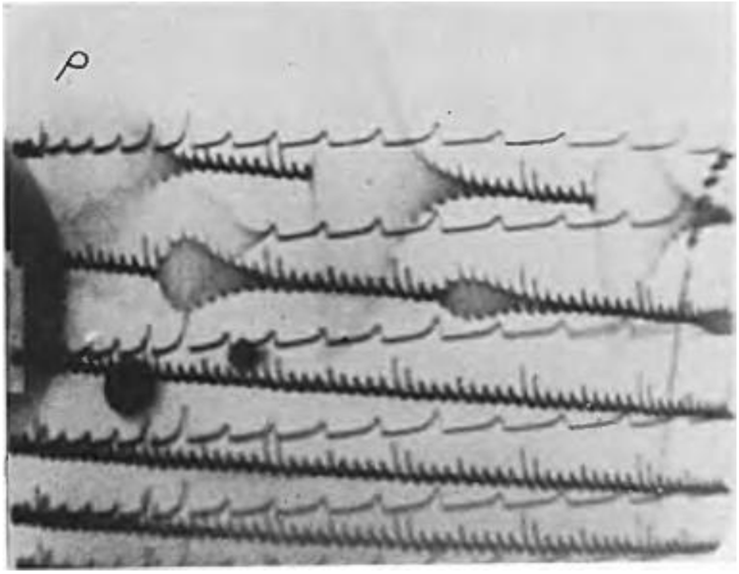

FIG. 18. Average grain size determination. Same as Fig. 17 but the brass was annealed at 1225°F and has an average grain size of .075 mm as measured by microscope. Although the sensitivity is the same as before, only six successive reflections are observable.

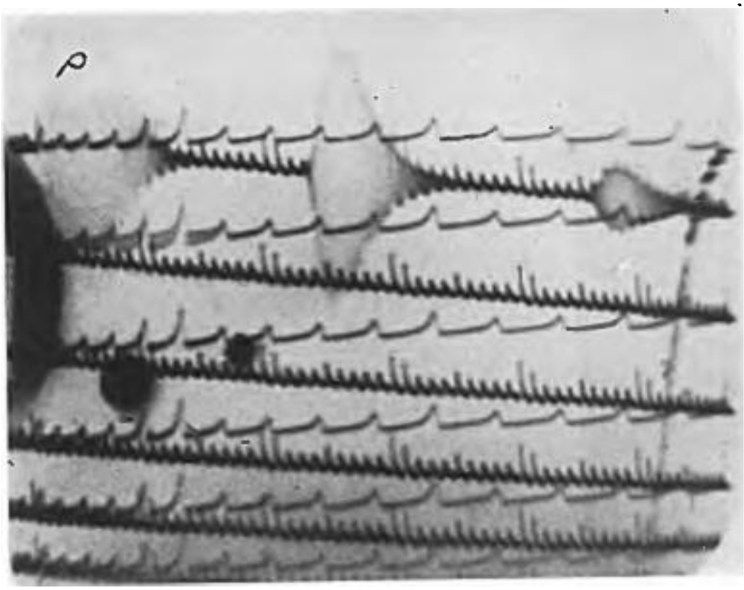

FIG. 19. Same as Fig. 17 except that the brass was annealed at 1350°F and has an average grain size of .105 mm as measured by microscope. Note that only three successive reflections are visible. Thus by suitable calibration, the rate at which the waves are scattered or absorbed may be used as a measure of average grain size. By proper choice of frequency and wave-length this method can be made sensitive in different ranges of grain size. The frequency used here was 5 mc corresponding to a wave-length in brass of 0.88 mm.

illustrative uses are set forth in the captions under the reflectograms.

ADDITIONAL REFINEMENTS

When the flaw is closer to the crystal than 0.5″, the waves reflected by the flaw may be received before the transmitted wave train ends, thus preventing the detection of the flaw. This problem has now been solved by special methods.

When the work is curved, the crystal may be ground to fit the curve as shown in Fig. 23. The waves then converge toward the center of the work and diverge beyond the center. All parts of the interior can be tested by moving the crystal around the surface. The curved crystal would be advantageous for instance in measuring the wall thickness of a pipe or tank.

Sometimes the flaw is so situated that there is no point on the surface of the piece at which a crystal can be placed and transmit waves to the

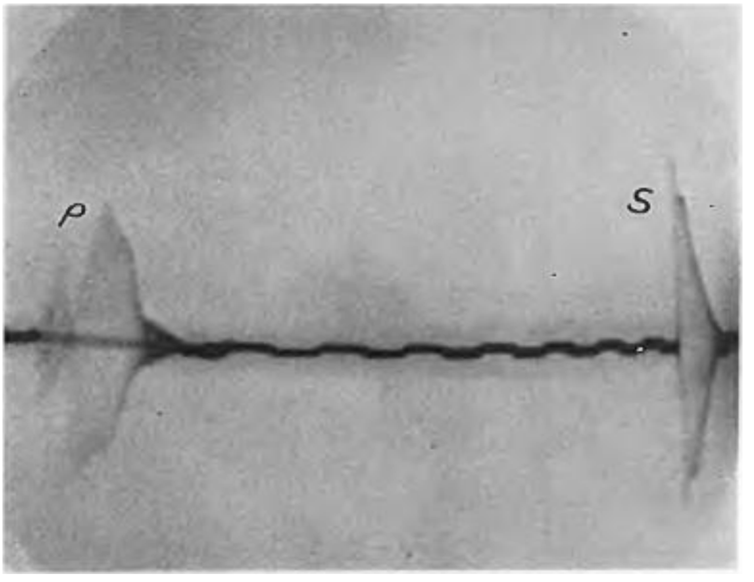

FIG. 20. Weld testing with Type B. Two pieces of 6″ diameter steel were electrically butt welded. *P* is the original pulse and *S* the reflection from the opposite end of the assembly 8.4″ from the crystal. This was taken at a place where the weld is continuous. Each square wave indicates one inch. Compare Figs. 21 and 22.

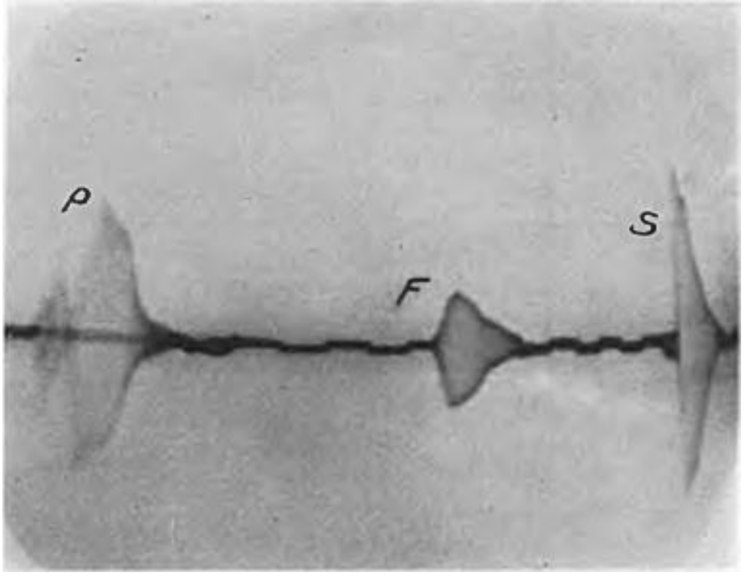

FIG. 21. Same as Fig. 20 but taken at a place where the weld was only partially continuous, yielding a reflection *F* from the weld and *S* from the other end.

flaw while sending the waves at right angles to the surface on which the crystal sits. Such is the case in railroad axles which sometimes develop fatigue cracks inside the wheel seat where the axle is of larger diameter than its end. Special devices have been developed whereby such flaws can be detected.

The reflectoscope is also provided with a connection for a second cable so that one crystal can be used for sending out the waves and a second crystal placed elsewhere for picking up the waves. Operation with a single crystal is so much more convenient however that the double crystal arrangement is seldom used.

When the surface of the work is quite rough, as for instance the surface of a casting, the crystal makes poor effective contact with the work and the sensitivity is considerably reduced.

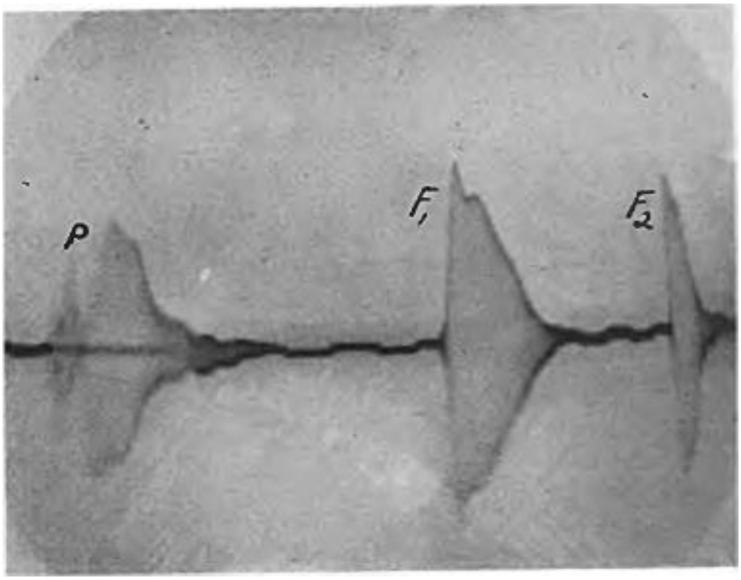

FIG. 22. Same as Fig. 20 but at a place where the weld is completely unfused. F_1 is the first reflection from the weld and F_2 the second.

It is advisable under these circumstances to touch a portable grinder to the surface. A rough turned surface is also sufficiently good.

If a crystal is placed against the wall of an empty tank, a long series of reflections back and forth through the metal wall will be obtained. When the tank is filled with liquid, the presence of the liquid against the inside face of the tank wall causes the successive reflections through the tank wall to be quickly absorbed so that only a *few* reflections are obtained. The level of liquid in a tank can therefore be determined merely by sliding the crystal up and down the outside of the tank wall and observing the level at which the number of successive reflections through the tank wall suddenly changes. Another procedure would be to mount the crystal permanently in the bottom of the tank and shoot the waves through the liquid, thereby obtaining a reflection from the upper surface of the liquid. The time of receipt of this reflection would be a measure of the height of the liquid column, although this would be influenced somewhat by liquid temperature and composition which would influence the velocity of sound in the liquid.

In the testing of rolled shapes, it is often most convenient to carefully inspect the billet from which the shapes are rolled; cropping out the flaws from the billet will keep them from being rolled out into the finished material. Since metal can be penetrated to a depth of the order of ten feet if the material is sound, large billets can be tested.

The reflectoscope can be used for determining holes or unfused areas in welds, but it does not directly measure the strength of the weld except insofar as the strength is influenced by the presence of such flaws or unfused areas. Certain cases have been observed where a weld was completely continuous and indicated no reflection on the reflectoscope, but was nonetheless found to be weak by breaking. The stresses produced by the sound waves are too feeble to break a weak weld.

I am indebted to Mr. Julian R. Frederick for his contributions during the many years which

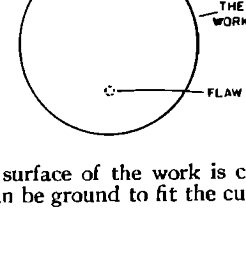

FIG. 23. If the surface of the work is curved the crystal can be ground to fit the curve.

he has spent in constructing and testing the intricate experimental equipment used in this development. I wish to acknowledge the contributions of Mr. William G. Langton, and the theoretical studies made by Mr. Daniel S. Ling, Jr.; also the contributions of Mr. Ralph B. DeLano, who has been responsible for much of the development of the Type B model, and of Mr. H. C. Drake, both of Sperry Products, Incorporated. This development has been supported through the Department of Engineering Research of the University of Michigan, by United Aircraft Corporation, General Motors Corporation, and for the last two years, by Sperry Products, Incorporated.

BIBLIOGRAPHY

Bergmann-Hatfield, *Ultrasonics and Their Scientific and Technical Applications* (John Wiley and Sons, New York, 1938), 264 pages.

Robert W. Wood, *Supersonics, the Science of Inaudible Sound* (Brown University Press, Providence, Rhode Island, 1939), 159 pages.

F. A. Firestone, "The Supersonic Reflectoscope for Interior Inspection," Metal Progress (Sept. 1945).

F. A. Firestone, United States Patent 2,280,226, granted April 1, 1942. Other patents pending.

Letter to the Editor

Cyril M. Harris
Bell Telephone Laboratories, Murray Hill, New Jersey
November 6, 1945

MEMBERS of the Acoustical Society are passing up an excellent opportunity for exchanging ideas with each other through the "Letters to the Editor" column. Very frequently one does research work which would be of interest to readers of this Journal but which is left unpublished because the researcher does not have the time to write an article or perhaps feels that his work is not sufficiently complete or important to warrant a paper. This column presents a medium, that we should take advantage of, for reporting such investigations.