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ULTRASONIC SPECTROSCOPY

TECHNICAL REPORT

by

OTTO R. GERICKE

DECEMBER 1966

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ULTRASONIC SPECTROSCOPY

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ULTRASONIC SPECTROSCOPY

ABSTRACT

Various experimental difficulties discussed in this report had to be overcome to be able to adopt spectroscopic procedures for ultrasonic testing and to construct an ultrasonic spectroscope. The ultrasonic pulse-echo spectroscope recently developed by the U. S. Army Materials Research Agency and its practical use for nondestructive inspection purposes are described. Test results obtained with the instrument indicate its usefulness for determining defect characteristics which cannot be revealed by conventional ultrasonic test methods. In addition, it is shown how the ultrasonic spectroscope can be used to distinguish microstructures of steel specimens.

CONTENTS

INTRODUCTION

In the realm of electromagnetic radiation, spectroscopic procedures have been on the scene for a considerable length of time and have proved to be extremely valuable for analyzing the chemical composition of materials. Hence, the adoption of spectroscopic techniques for ultrasonic testing to improve existing methods appears to be a logical step. But, in order to develop a practical test instrument for this purpose, certain experimental difficulties have to be overcome.

The greatest obstacle encountered in the ultrasonic field is the limited frequency response of electromechanical transducers used for the transmission and reception of ultrasonic signals. Only in recent years have piezoelectric transducer materials become available which provide a wider frequency response without excessive loss in conversion sensitivity.

In view of the great success of the ultrasonic pulse-echo test technique, it is desirable to combine the spectroscopic method with a pulse-echo procedure. This, unfortunately, introduces additional experimental difficulties due to the intricate electronic circuitry required.

EQUIPMENT FOR ULTRASONIC SPECTROSCOPY

Three years of extensive research and engineering work were required to overcome the experimental problems. A practical instrument for ultrasonic spectroscopy is now available and shall be described briefly before discussing its applications, which are the main subject of this report. A more detailed account of the various equipment design factors can be found in an earlier report.[1]

Figure 1 illustrates a simplified block diagram of the ultrasonic spectroscope. The instrument comprises a rectangular pulse generator, a wide

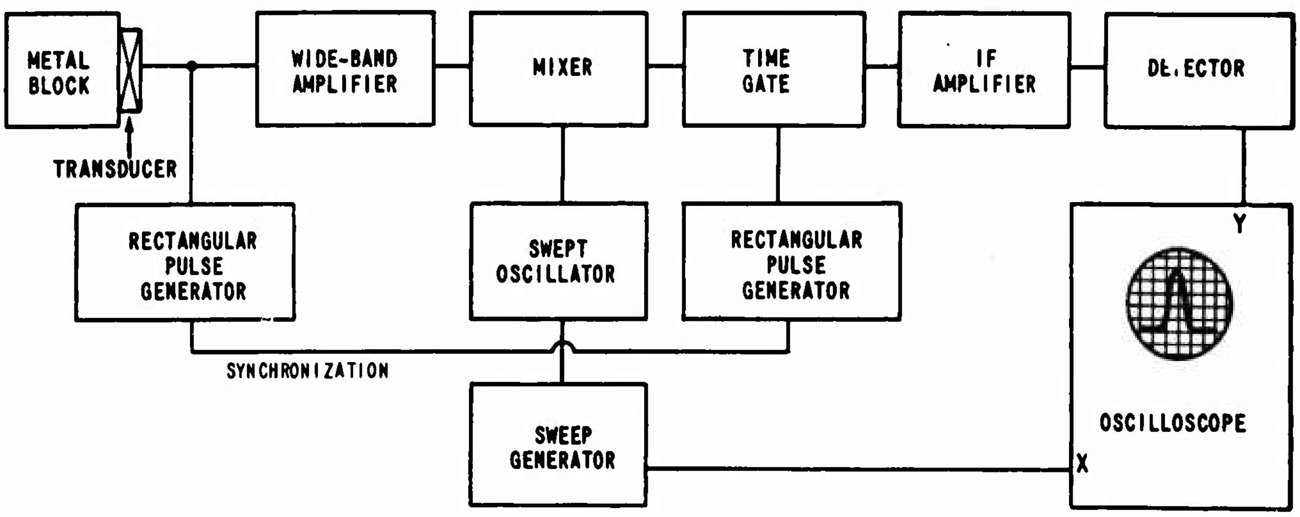

Figure 1. Schematic block diagram of ultrasonic pulse-echo spectroscope

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[1] GERICKE, OTTO R. *Ultrasonic Spectroscopy of Steel.* U. S. Army Materials Research Agency, AMRA TR 64-44, December 1964.

band amplifier, and a time-gated electronic spectrum analyzer. The pulse generator excites a lead zirconate niobate transducer to emit short bursts of ultrasonic vibrations that contain various frequency components covering a band of about 3 to 10 megacycles. After transmission of the initial pulse, the transducer acts as a wide-band receiver and picks up multifrequency echoes returning from the specimen to which it is coupled.

The purpose of the time gate connected between the wide-band amplifier and the spectrum analyzer is to enable the selection of a particular echo return for spectrum analysis. The echo reflected by a defect located within the specimen, for example, can be analyzed without interference from the initially transmitted pulse or other echoes such as reflections from specimen boundaries.

Important for a proper functioning of the ultrasonic spectroscope is the nature of the spectrum of the initially transmitted ultrasonic pulse. This spectrum, which, in the following, shall be referred to as the basic pulse spectrum, is determined by two factors: the length of the rectangular excitation voltage pulse applied to the transducer, and the frequency response characteristic of the transducer itself. If the excitation pulse length is properly matched to the transducer response curve, a sufficiently uniform ultrasonic spectrum can be generated to permit successful ultrasonic spectroscopy.

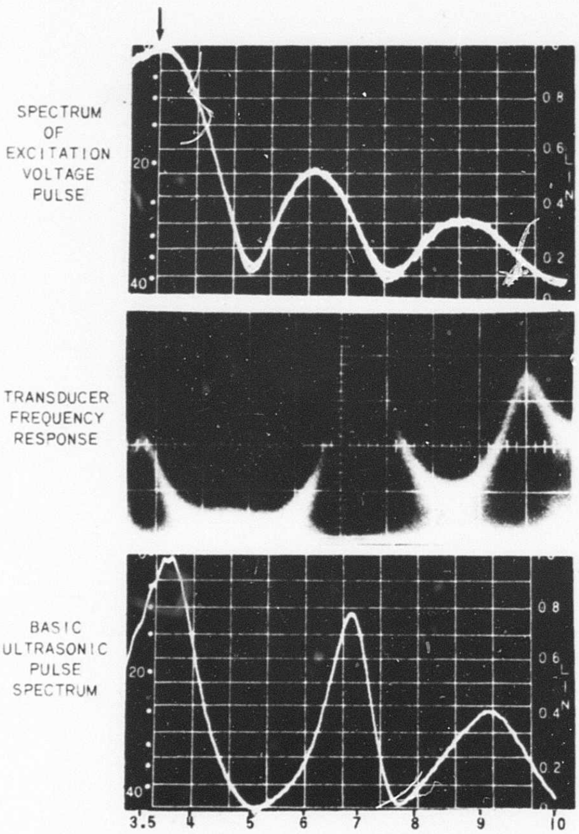

Figure 2. Spectrum of rectangular excitation voltage pulse of 0.42 μ sec duration, transducer frequency response curve for transmission and reception (loop response), and generated ultrasonic pulse spectrum (basic spectrum)
19-066-231/AMC-66

Figure 2 illustrates the matching process. The first trace which, like the two others, is a linear plot (on an arbitrary scale) of spectral amplitude versus frequency, shows the excitation pulse spectrum. The second trace represents the transducer loop response curve obtained by a method described elsewhere.[2] The third trace, finally, depicts the spectrum that appears on the spectrum analyzer if both the reflector and the specimen microstructure are such that they do not alter the spectral amplitude distribution of the initially transmitted pulse. These conditions are met for a back-echo from a thin aluminum plate with smooth parallel surfaces.

[2]GERICKE, OTTO R. *Experimental Determination of Ultrasonic Transducer Frequency Response.* U. S. Army Materials Research Agency, AMRA TR 66-27, September 1966.

The basic pulse spectrum as it appears in Figure 2 consists of three frequency lobes with peaks at 3.7, 6.9, and 9.2 megacycles, which are similar to the broad spectral lines encountered in optics.

EXPERIMENTS

Test Specimens

The practical potential of the spectroscopic technique can best be examined by comparing it with a conventional pulse-echo test. To establish controlled experimental conditions for this comparison, test specimens containing artificial flaws of known configurations are used. Figure 3 schematically illustrates the geometry of test blocks and artificial flaws fabricated for this purpose. The blocks are cylindrical and have polished top surfaces to provide optimum coupling conditions for the ultrasonic transducer. They are made of aluminum because in the desired frequency range aluminum exhibits very little attenuation for ultrasound and the chance that the pulse spectrum is distorted due to frequency selective losses in the block material is therefore minimized.

Three sets of test blocks are used which differ with respect to flaw geometry. One set contains flaws whose surfaces are parallel to the test surface (α = 0 degrees in Figure 3). In the second set of blocks, the defect surfaces are oriented at an angle of 10 degrees with respect to the test surface (α = 10 degrees in Figure 3). The third set is provided with cylindrical holes (see right hand drawing in Figure 3) drilled parallel to the test surface.

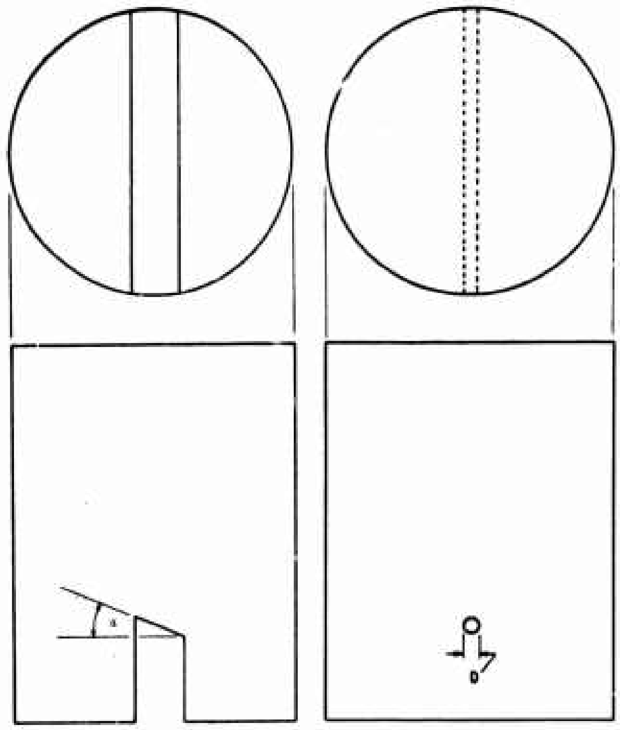

Figure 3. Configuration of cylindrical test blocks provided with (left) cuts of 0 and 10 degree orientation with respect to the top block surface and (right) cylindrical holes drilled parallel to the top block surface

19–066–235/AMC–66

Each set is comprised of four blocks with defects of four different sizes. While the length of all defects is the same, the width of their cross-sectional projection onto the test surface is 5/8, 5/16, 5/32, and 5/64 inch.

Conventional Test Results

A conventional ultrasonic pulse-echo test yields the flaw location, which can be derived from the pulse travel time, and also the flaw-echo amplitude. The latter is a function of the ultrasound reflectivity of the flaw.

Whether the defect reflectivity can be correlated to the defect size or not is a question which shall be experimentally investigated using the above-described blocks as test specimens.

To this end, a 5-megacycle, 3/4-inch-diameter barium titanate transducer is connected to a commercial pulse-echo test instrument of late design and is sequentially coupled to the various test blocks. Defect-echo heights measured in these tests are shown in a bar chart in Figure 4, where the height of each bar is equal to the measured defect-echo amplitude plotted on a logarithmic scale calibrated from -60 to 0 decibels. The three groups of bars correspond to the three sets of test blocks representing the three different geometries.

An examination of the test results presented in Figure 4 points up two important facts. First, one notes that a consistent correlation between defect-echo height and defect size is possible only if the defect surface is parallel to the test surface - a condition represented by the first set of bars. The second observation is that the defect-echo amplitude is not solely a function of the defect magnitude but also depends upon other geometrical

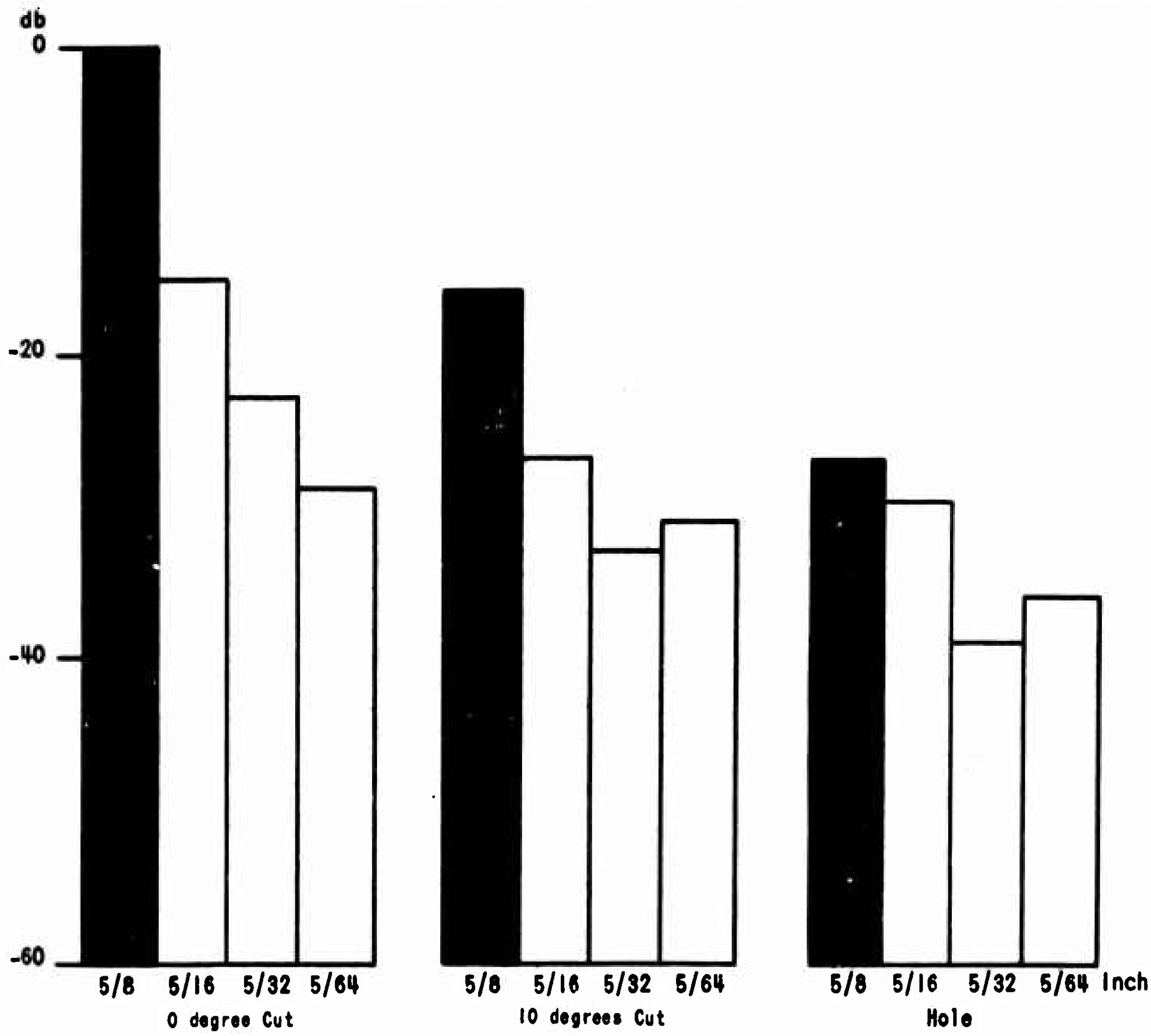

Figure 4. Defect-echo amplitudes obtained by conventional ultrasonic pulse-echo testing

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factors such as flaw orientation and shape. For instance, the 5/64-inch-wide 0-degree cut produces an indication which is larger than the echo obtained for the 5/16-inch-diameter hole.

Thus, the data shown in Figure 4 is remarkable in one respect: it demonstrates the inability of the conventional pulse-echo test to provide conclusive data on defect sizes unless the defects are known to be strictly laminar.

This dilemma has led to a growing lack of confidence in the ultrasonic test method and justifies the intensive effort made at the U. S. Army Materials Research Agency to develop a more refined ultrasonic inspection method which, it is felt, can be provided by the spectroscopic technique.

Spectroscopic Examination of Test Blocks with Artificial Defects

The application of the ultrasonic pulse-echo spectroscope for the examination of the fabricated test blocks produces some very significant results.

The basic pulse spectrum shown in Figure 2 will be repeated for reference purposes in some of the following figures which illustrate the spectroscopic data obtained for the various test blocks. To eliminate the influence of the overall defect reflectivity which determines the defect-echo height in conventional testing and does not prove conclusive, all defect-echo spectra are normalized. That is, the wide-band amplifier gain in each case is so adjusted that regardless of overall defect reflectivity, the frequency component with the highest amplitude produces a full-scale vertical deflection on the cathode ray tube of the spectrum analyzer.

First, spectra obtained for test blocks representing a certain flaw geometry but four different flaw sizes are presented. Figure 5 illustrates echo spectra of all flaws whose surface is oriented parallel to the test surface. One notes that the spectra obtained for the 5/8- and 5/16-inch-wide defects do not materially deviate from the basic pulse spectrum. However, as the defect width decreases to 5/32 and 5/64 inch, medium and high frequency (6 to 10 megacycles) components gain on low frequency (3.5 to 4.5 megacycles) components in the spectrum.

This shift in spectral amplitude distribution can easily be explained. As the width of the flaw decreases, it approaches the magnitude of the ultrasonic wavelength at the low frequency end of the spectrum and, as a result, the defect reflectivity for these low frequencies falls off. At 4 megacycles, for instance, the wavelength in aluminum is equal to 4/64 inch and, therefore, almost equivalent to the width of the smallest defect (5/64 inch).

Defect-echo spectra for the second set of blocks which contain flaws oriented at 10 degrees relative to the test surface are shown in Figure 6. In this case, one observes a predominance of the low frequency components of the spectrum, especially for the larger defect sizes. This is the result of ultrasonic beam divergence which is greater at lower frequencies so that low frequencies, upon reflection from an angulated defect, are not as effectively deflected away from the transducer as the better collimated medium and high frequencies. However, as the defect size decreases, the influence of the ultrasonic wavelength begins to be felt because the low frequency reflectivity diminishes relative to the medium and high frequency reflectivity. The net result is that for relatively small angulated flaws the spectrum again approaches the shape of the basic pulse spectrum, but not quite, since the effect of flaw angulation is evidently stronger than the effect of flaw size.

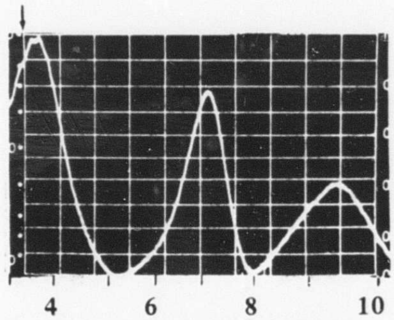
Spectroscopic data obtained for the third set of blocks which contain cylindrical holes is shown in Figure 7. Again defect-echo spectra exhibit a characteristic amplitude distribution which differs from the shape of the basic pulse spectrum and also changes with the defect diameter. For a 5/8-inch-wide hole, low and high frequency components are depressed relative to the medium frequencies (6 to 8 megacycles). For smaller hole diameters, however, weaker medium and high frequency components are observed than are contained in the basic pulse spectrum.

Spectroscopic test results thus far presented indicate that the amplitude distribution in the defect-echo spectrum is a function of the *total* configuration of the defect including its size. Each of the three defect geometries examined produces characteristic spectral signatures. This (as the following examples will illustrate) makes it possible to differentiate between flaws which, in a conventional test, yield identical or almost identical echo heights but differ in size.

Referring again to Figure 4 which presents the conventional pulse-echo test information, attention is directed toward the data for the 5/16-inch-wide 0-degree cut and the 5/8-inch-wide 10-degree cut. One notes that these two defects, although different in size, produce echo indications that deviate only by 1 decibel from each other. Hence, it is of great interest to examine the information provided by the spectroscopic test in this case.

Figure 8 illustrates the echo spectra obtained for the two defects and also the basic pulse spectrum. The echo spectrum of the 5/16-inch-wide 0-degree cut resembles the basic pulse spectrum very closely, while the 5/8-inch-wide 10-degree cut lacks amplitude in the medium and high frequency ranges. This indicates that the first flaw evidently reflects all spectral components equally well, while the geometry of the other flaw is such that the reflectivity decreases with frequency. This explains why, in a conventional test, the second flaw, although larger, produces about the same echo height.

If flaw sizes were unknown, the reasoning would have to be reversed. According to Figure 8, the first flaw exhibits an undistorted spectrum while the second flaw does not. Thus, the second flaw must possess a configuration which is less favorable for the reflection of ultrasound. A comparison of defect-echo heights derived from an ordinary pulse-echo test cannot be expected to yield valid information on actual defect magnitudes.



Basic Pulse Spectrum

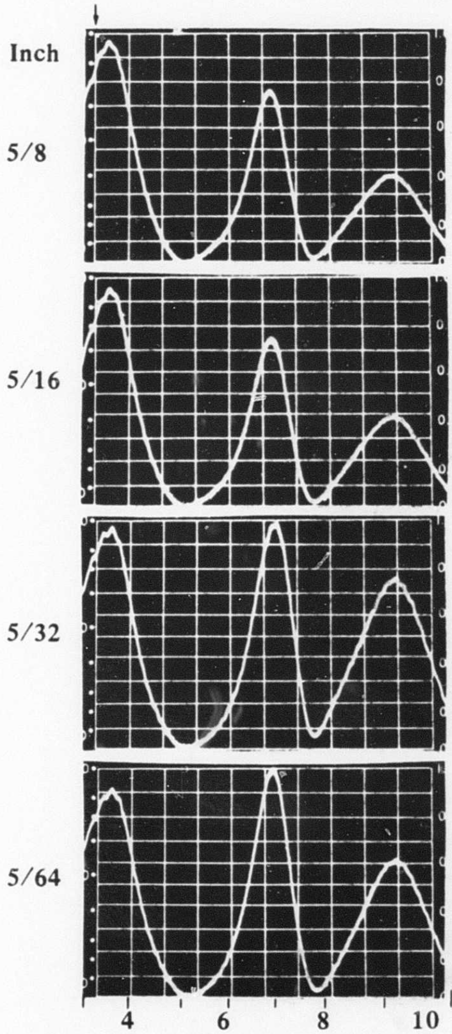


Figure 5. Ultrasonic spectra obtained for echoes reflected from defects of various widths (as indicated) whose surfaces are parallel to the test surface

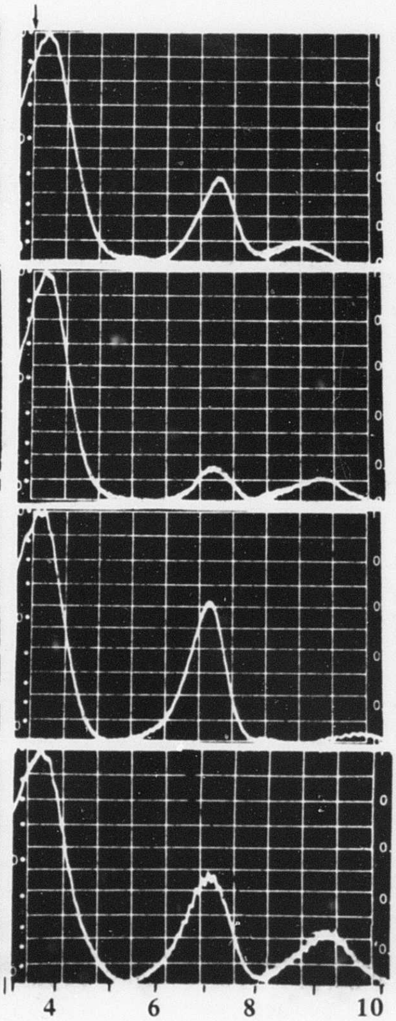


Figure 6. Ultrasonic spectra obtained for echoes reflected from defects of various widths (as indicated) whose surfaces are oriented at an angle of 10 degrees with respect to the test surface

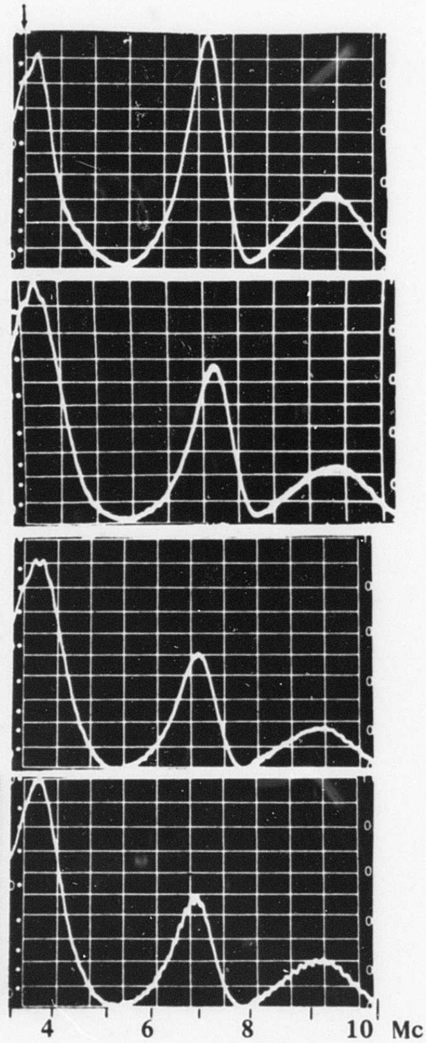
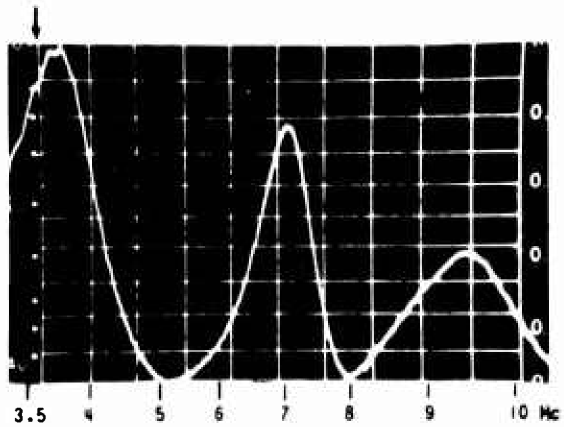


Figure 7. Ultrasonic spectra obtained for echoes reflected from cylindrical holes of various diameters (as indicated) drilled parallel to the test surface

The quoted example demonstrates how errors concerning flaw size, which are inherent in the conventional pulse-echo test, can be avoided through flaw-echo spectrum analysis.

A further example for effective defect discrimination provided by the spectroscopic technique is shown in Figure 9. Here, defect-echo spectra of the 5/64-inch-wide 0-degree cut and the 5/16-inch-diameter hole are contrasted with each other. According to Figure 4, the echo heights for these two flaws differ by only 1 decibel.



BASIC PULSE SPECTRUM

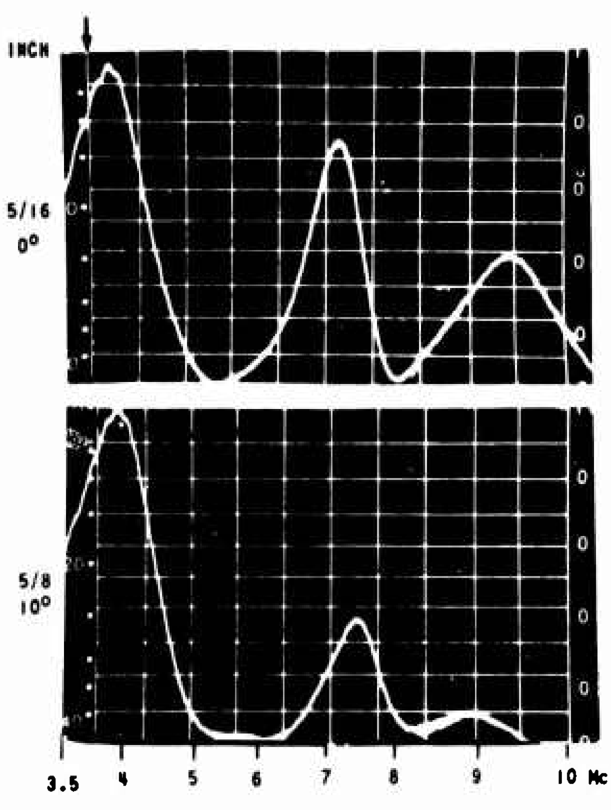


Figure 8. Ultrasonic spectra obtained for 5/16-inch-wide defect oriented parallel (0°) to the test surface and 5/8-inch-wide defect oriented at an angle of 10° with respect to the test surface.

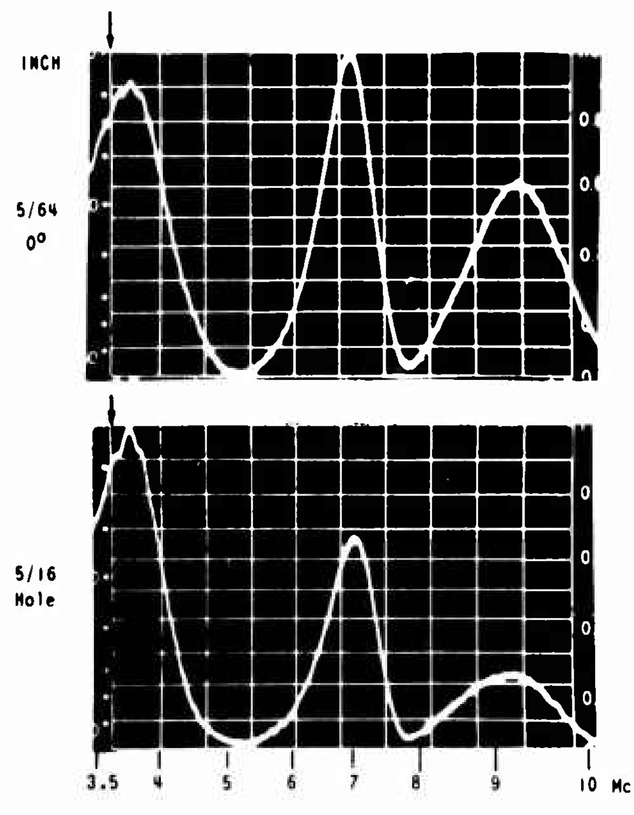


Figure 9. Ultrasonic spectra obtained for 5/64-inch-wide defect oriented parallel (0°) to the test surface and 5/16-inch-diameter cylindrical hole drilled parallel to the test surface.

Compared with the basic pulse spectrum, the first flaw spectrum exhibits larger medium and high frequency components. According to Figure 5, this is indicative of a favorable flaw orientation but a relatively small flaw size. The second defect-echo spectrum of Figure 9, on the other hand, exhibits reduced medium and high frequency components which points to a less favorable geometry for overall ultrasound reflection. Thus, it is not surprising that the 5/16-inch flaw, although much greater than the other flaw, does not produce a larger echo in a conventional test. Again, the example shows how the spectroscopic method helps to avoid a gross error in defect size which would result from an interpretation of ordinary test data.

It should be emphasized that the geometrical differences of the examined artificial flaws are not really dramatic. Their lengths, for instance, are identical. The change in orientation is only 10 degrees, and flat flaw surfaces are compared with cylindrical rather than spherical flaw surfaces. Situations involving similar geometrical differences are easily encountered in practical testing.

Spectroscopic Differentiation of Steel Microstructure

The spectroscopic pulse-echo test method has another nondestructive test application which has been discussed in detail in an earlier publication.[3] By analyzing the spectra of back echoes obtained for steel specimens having parallel surfaces one can determine differences in their grain structure.

The test is based on the frequency dependence of losses encountered by ultrasonic signals when they pass through certain polycrystalline substances such as steel.

An example for this application is given in Figure 10 which shows ultrasonic back-echo spectra obtained for two steel specimens having different grain sizes. The spectra differ from those shown earlier in two respects. The spectral amplitude is plotted on a logarithmic rather than linear scale and the frequency range extends from 3 to 12 megacycles due to a wider frequency response of the ultrasonic transducer.

The first spectrum shows the spectral amplitude distribution of the back-echo obtained in the case of a relatively fine-grained structure. The second trace shows a similar spectrum obtained for a coarser steel microstructure. The coarser grain causes the spectral amplitude to decrease with increasing ultrasonic frequency and can thus be nondestructively determined. The effect begins to be felt at around 7 megacycles and becomes more pronounced in the upper frequency range of the spectrum.

The spectroscopic test provides a very fast differentiation of grain sizes and has the further advantage that it can be applied even in cases where, due to high ultrasonic attenuation, multiple back echoes cannot be obtained.

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[3] GERICKE, OTTO R. *Ultrasonic Spectroscopy of Steel.* Materials Research and Standards, v. 5, no. 1, January 1965, p. 23-30.

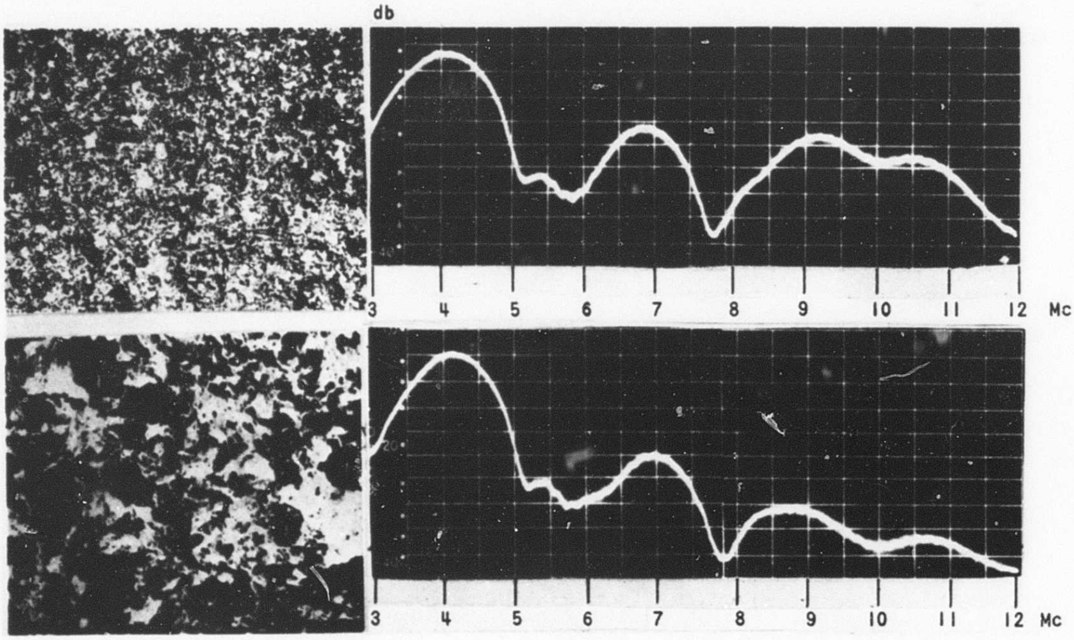

Figure 10. Steel microstructure and associated ultrasonic spectrum, spectral amplitude is plotted on a logarithmic (0 to -40 db) vertical scale versus frequency in megacycles on the horizontal scale.
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SUMMARY AND CONCLUSIONS

The experimental results presented in this report illustrate the practical usefulness of the spectroscopic method. The spectroscopic analysis of defect echoes yields more information on the defect configuration than is available from ordinary pulse-echo test techniques. Thus, serious errors concerning defect size can be avoided.

Ultrasonic spectroscopy also affords a new and more effective approach to ultrasonic attenuation testing and can be used to sort steel according to grain size.

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