NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.
WATERTOWN ARSENAL LABORATORIES

GEOMETRY OF HIDDEN DEFECTS DETERMINED BY ULTRASONIC PULSE ANALYSIS AND SPECTROSCOPY

TECHNICAL REPORT WAL TR 830.5/5

BY

OTTO R. GERICKE

DATE OF ISSUE - DECEMBER 1962

ON5 CODE 6010.11.838
BASIC RESEARCH IN ENGINEERING SCIENCES
D/A PROJECT 68925001

WATERTOWN ARSENAL
WATERTOWN 72, MASS.
The findings in this report are not to be construed as an official Department of the Army position.

ASTIA AVAILABILITY NOTICE
Qualified requesters may obtain copies of this report from ASTIA

DISPOSITION INSTRUCTIONS
Destroy; do not return
GEOMETRY OF HIDDEN DEFECTS DETERMINED BY
ULTRASONIC PULSE ANALYSIS AND SPECTROSCOPY

Technical Report WAL TR 830.5/5

By
Otto R. Gericke

Date of Issue - December 1962

OMS Code 5010.11.838
Basic Research in Engineering Sciences
D/A Project 59925001

WATERTOWN ARSENAL
WATERTOWN 72, MASS.
A novel ultrasonic test method is described utilizing ultrasonic signals which contain a broad band of frequencies, and, in analogy to optics, can therefore be considered as "white" ultrasonic pulses. The form and spectral energy distribution, or "color", of such ultrasonic pulses is influenced by the geometry of a defect from which they are reflected. Hence, an analysis of the defect echo yields information on the defect configuration.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>3</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>3</td>
</tr>
<tr>
<td>THEORETICAL INVESTIGATION</td>
<td>4</td>
</tr>
<tr>
<td>PRELIMINARY EXPERIMENTS</td>
<td>6</td>
</tr>
<tr>
<td>APPLICATION</td>
<td>6</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>11</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>12</td>
</tr>
</tbody>
</table>
INTRODUCTION

Defects concealed in metals or other solid materials can be detected by ultrasonic inspection. The test procedure predominantly employed for this purpose is generally referred to as the ultrasonic pulse echo method and is in principle quite similar to the Sonar echo sounding technique used in submarine warfare. However, the range of ultrasonic frequencies employed for material inspection is different and extends from about 0.2 to 100 megacycles.

In the ultrasonic pulse echo method, a single ultrasonic transducer acts as transmitter and receiver of ultrasonic signals. The transducer, which is coupled to the surface of the test specimen, transmits a pulse of ultrasonic energy into the specimen and is then ready to receive any echoes reflected from internal defects or from the back surface of the specimen. The received echoes are amplified and displayed as vertical indications on a cathode ray tube. The X-deflection plates of the cathode ray tube are usually connected to a time base generator to provide a means for measuring the travel time of the initially transmitted ultrasonic pulse from the transducer to a specific defect. From the knowledge of the travel time the distance between the defect and the test surface can be deduced, if the velocity of ultrasonic waves in the tested material has previously been determined. The two remaining coordinates of the defect location can be derived by scanning the test specimen surface with the ultrasonic transducer and noting the position at which the defect echo amplitude is the largest. If the defect is much greater than the width of the ultrasonic beam used for scanning the test specimen, the procedure will even yield the geometric outline of the defect. In this case it is generally easy to assess the severity of a flaw on the basis of the ultrasonic test results. However, if the flaw is of the same order of magnitude or smaller than the beam width, the flaw geometry is not revealed by the pulse echo test and the interpretation of test results is, therefore, quite a problem.

In the past, numerous attempts have been made by researchers to determine the size of defects which are smaller than the ultrasonic beam width. (In the near radiation field, the beam width is equal to the ultrasonic transducer diameter). One such attempt is to compare the defect echo amplitude to indications derived from artificial flaws of known size. Although great efforts have been expended on this approach, in most cases the results are not satisfactory.

A different technique, which has received much less attention because of experimental difficulties, offers more promise as a solution to the problem. In this technique, pulse echo tests are carried out at various ultrasonic frequencies rather than at only one particular frequency. Thus, the specimen is subjected to ultrasound having different wavelengths. Since the reflection of ultrasonic energy from a
defect depends on the ratio of the defect magnitude to the ultrasonic wavelength, the defect echo amplitude is influenced by changes of the ultrasonic wavelength. A determination of the frequency dependence of the defect echo amplitude will, therefore, yield information on the defect geometry.

Unfortunately, the practical application of the aforementioned concept has certain difficulties. Although most commercial pulse echo test instruments are so designed that they can be adjusted for various ultrasonic frequencies, the successive application of different ultrasonic frequencies to a single test specimen would be very cumbersome. Retuning of the transmitter and/or amplifier would be required and, in addition, exchanging of the transducers would be necessary. The latter necessity is a most objectionable feature of the successive procedure because by changing transducers a variation of the transducer-to-specimen coupling conditions may be introduced and, thus, the reliability of the test may be impaired.

To overcome the difficulties encountered with procedures employing a successive application of different ultrasonic frequencies, a novel method was developed at Watertown Arsenal Laboratories which permits the simultaneous use of a wide range of ultrasonic frequencies in pulse echo testing.

THEORETICAL INVESTIGATION

The first step in the development of the novel multifrequency pulse echo test was to investigate how ultrasonic signals could be produced which would contain energy covering a wide range of frequencies. A theoretical study of this problem revealed that single polarity as well as carrier frequency pulses having a rectangular outline would be suitable as sources of multifrequency or, to borrow a term from optics, "white" energy. The spectral energy functions for two representative pulses of such type are given by the equations shown in Figure 1. Figure 2 shows the spectra derived from the formulae of Figure 1 for the two basic pulses (Figures 2a and 2b) and for a carrier frequency pulse that comprises three cycles (Figure 2c). Absolute spectral amplitudes are plotted on a logarithmic scale versus frequency on a linear scale. The reason for selecting this type of plot was that curves thus obtained, to a large extent, resembled displays produced by the electronic spectrum analyzer available for the experimental work.

Comparison of the spectra depicted by Figure 2 indicates that the third pulse, consisting of three cycles of the carrier frequency, contains higher frequencies at about the same level as the two other pulses. Although the spectral amplitude in the vicinity of the carrier frequency is relatively larger, the 3-cycle pulse can still be regarded as a fairly "white" signal. This result is of practical importance because the
Figure 1. SPECTRAL FUNCTIONS $A(f)$ AND $A'(f)$ OF SINGLE POLARITY AND CARRIER FREQUENCY PULSES WITH RECTANGULAR ENVELOPES

$A_o$ = Pulse Amplitude; $D$ = Pulse Length; $f$ = Frequency; $f_o$ = Carrier Frequency

$A(f) = \frac{A_o D}{\pi} \frac{\sin \pi Df}{\pi Df}$

$A'(f) = \frac{A_o D}{2\pi} \frac{\sin \pi D(f - f_o)}{\pi D(f - f_o)}$

Figure 2. SPECTRA OF SINGLE POLARITY AND CARRIER FREQUENCY PULSES WITH RECTANGULAR ENVELOPE

FREQUENCY RANGE, MEGACYCLES PER SECOND
generation of an ultrasonic signal consisting of three cycles proved to be feasible.

**PRELIMINARY EXPERIMENTS**

By applying rectangular voltage pulses of single polarity to barium titanate transducers it was possible to produce "white" ultrasonic pulses similar to the last pulse illustrated by Figure 2. Other piezoelectric materials which were also examined did not yield equally favorable results. The upper trace of Figure 3 shows an ultrasonic signal and its spectrum obtained with a transducer having less desirable characteristics. The pulse exhibits a build-up and decay of the oscillation slower than demonstrated by the lower trace of Figure 3 which was derived from the specially selected barium titanate transducer. Correspondingly, the spectra of the two pulses show significant differences. While the upper spectrum can be considered as almost monochromatic, the lower spectrum exhibits a relatively large content of higher frequencies. Although the energy distribution in the spectrum differs somewhat from the theoretical case illustrated by Figure 2, the signal obtained from the barium titanate transducer proved to be quite useful as a "white" pulse for the purpose of relative defect geometry analysis.

**APPLICATION**

"White" ultrasonic pulses of the type illustrated by the lower trace of Figure 3 were employed for experiments on specimens with fabricated
flaws of various geometries. The experiments were carried out with compressional ultrasonic waves and relatively large specimens. The velocity of ultrasonic waves could, therefore, be regarded as a material constant. Hence, the ultrasonic wavelength was inversely proportional to the frequency. Since aluminum specimens were used, the wavelength of a 10-megacycle signal, for instance, was 0.024 inch.

The purpose of the first series of experiments was to demonstrate that "white" ultrasonic pulses were superior to monochromatic test signals with regard to their ability to determine the configuration of hidden defects. The same pair of test specimens was, therefore, subjected to an inspection by the two different test systems schematically outlined by Figure 4. The system depicted by Figure 4a possesses a relatively narrow band width and, hence, uses essentially monochromatic ultrasonic energy. The pulse associated with the narrow band width system is relatively long and has a round contour. A test system which utilizes wide band width components is shown by Figure 4b together with the much shorter ultrasonic pulse it produces.

![Figures 4](image)

Figures 5 and 6 illustrate the results obtained from the inspection of two aluminum test specimens provided with cylindrical holes of 1/8- and 1/32-inch diameter respectively. (In this and in all the following experiments, the amplifier gain was so adjusted that the peak amplitudes of the defect echoes were always the same, thus facilitating comparisons of pulse shapes and pulse spectra.)
Figure 5. ULTRASONIC REFLECTIONS OBTAINED FROM 1/8-INCH AND 1/32-INCH HOLES WITH A NARROW-BAND TEST INSTRUMENT

Figure 6. ULTRASONIC REFLECTIONS OBTAINED FROM 1/8-INCH AND 1/32-INCH HOLES WITH A WIDE-BAND TEST INSTRUMENT
Figure 5, which shows defect echoes obtained with the narrow band width system, indicates that no significant differences in pulse contour could be observed if the 1/8-inch and 1/32-inch holes reflected monochromatic pulses. In contrast to this result, the pulse shapes and spectra of "white" pulse reflections, which are illustrated by Figure 6, show significant differences. The distinguishing characteristic of the pulse shapes are the amplitudes of the second cycles indicated by markers on Figure 6. In addition, the pulse spectra exhibit pronounced differences, a fact which is not surprising because, according to the Fourier theory, the time function can be strictly correlated to the frequency function. (Spectra of Figures 6, 7, and 8 cover a range of 5 to 15 mcps.)

In evaluating the results illustrated by Figure 6, it is important to note that the two cylindrical flaws, which closely represent the practical case of stringer inclusions, had equal length and differed only in diameter. Hence, the fact that it is possible to distinguish between these flaws is quite significant.

Further experiments were carried out by applying the "white" pulse test method to aluminum cylinders provided with axially drilled flat-bottom holes as indicated by Figure 7. These artificial defects were introduced into the specimens to simulate internal porosity. The pulse shapes and spectra derived from such defects are shown by Figure 7. On the basis of these test results, it is possible to distinguish between a porosity consisting of a large number of small holes and a porosity consisting of a small number of large holes, although the total reflecting cross-section in each case is about the same. Information concerning the size of the individual cavities which can thus be obtained is very important for practical quality inspection because small holes can sometimes be eliminated by a subsequent forging process while large holes would be a basis for rejection of the part under inspection.
As a final example of applications for the ultrasonic pulse analysis method the inspection for internal cracks is considered. The interpretation of ultrasonic test results obtained from specimens having internal cracks is extremely difficult if conventional monochromatic methods are employed. This difficulty exists because by such methods only the amplitude of the reflection is available as a criterion. The echo amplitude, however, is strongly influenced by the orientation of the crack with reference to the surface of the specimen to which the transducer is coupled. A relatively large crack, for instance, is liable to be misinterpreted as being an insignificant defect if it is so oriented that at the specific test frequency only a small amount of ultrasonic energy is reflected back to the transducer. In the pulse analysis technique, however, errors of this nature are less likely to occur because amplitude differences between individual frequency components of a "white" ultrasonic signal yield additional information.

To investigate the effectiveness of the pulse analysis method for the inspection of internal cracks, the aluminum specimens illustrated in Figure 8 were prepared. The specimens contained cuts at angles of 10,
20 and 30 degrees to the test surface to simulate internal cracks of various orientations. Figure 8 shows also the defect echo and echo spectrum obtained from each specimen and it is noted that pulse shapes and spectra exhibit very significant differences for the various defect orientations.

CONCLUSIONS

The results of the experiments conducted indicate that the effectiveness of ultrasonic pulse echo testing can be greatly enhanced by the introduction of multifrequency signals and defect echo analysis. The main benefit to be derived from this innovation is that differences in the configuration or orientation of concealed defects can be determined.
BIBLIOGRAPHY

Pertinent literature containing certain details of work summarized in this report are listed:


MAGUIRE, J. J., Determination of Flow Geometry by Ultrasonic Pulse Contour and Spectrum Analysis, Watertown Arsenal Laboratories, WAL TR 830.5/2, July 1961.
### Technical Report Distribution

**Report No.:** WAL TR 830.5/5  
**Title:** Geometry of Hidden Defects Determined by Ultrasonic Pulse Analysis and Spectroscopy  
**December 1962**

Distribution List approved by 1st Indorsement from Ordnance Weapons Command, ORDOW-TB, dated 4 January 1962

<table>
<thead>
<tr>
<th>No. of Copies</th>
<th>To</th>
</tr>
</thead>
</table>
| 1             | Office of the Director of Defense Research and Engineering, Room 3D-1067, The Pentagon, Washington 25, D.C.  
                ATTN: Mr. J. C. Barrett |
| 10            | Commander, Armed Services Technical Information Agency, Arlington Hall Station, Arlington 12, Virginia  
                ATTN: TIPDR |
                ATTN: Dr. G. Mock |
| 1             | Solid Propellant Information Agency, Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland |
| 1             | Commanding General, U.S. Army Materiel Command, Washington 25, D.C.  
                ATTN: AMCRD-RS |
| 2             | Commanding General, U.S. Army Missile Command, Redstone Arsenal, Alabama  
                ATTN: AMSMI-RB, Redstone Scientific Information Center |
| 1             | AMSMI-RRS, Mr. R. E. Ely |
| 1             | AMSMI-RKX, Mr. R. Fink |
| 1             | AMSMI, Mr. W. K. Thomas |
| 1             | AMSMI-RSM, Mr. E. J. Wheelahan |
| 1             | Commanding General, U.S. Army Mobility Command, Detroit 9, Michigan |
| 1             | Commanding General, U.S. Army Munitions Command, Dover, New Jersey |
| 1             | Commanding General, U.S. Army Test and Evaluation Command, Aberdeen Proving Ground, Maryland  
                ATTN: AMSTE, Coating and Chemical Laboratory |
| 1             | AMSTE, Technical Library |
Commanding Officer, Diamond Ordnance Fuze Laboratory, Washington 25, D. C.
1
ATTN: AMXDO-TIB

Commanding Officer, Frankford Arsenal, Philadelphia 37, Pennsylvania
1
ATTN: ORDBA-1330
1
ORDBA-0270, Library

Commanding Officer, Picatinny Arsenal, Dover, New Jersey
1
ATTN: AMSMU, Mr. J. J. Scavuzzo, Plastics and Packaging Laboratory

Commanding Officer, PLASTEC, Picatinny Arsenal, Dover, New Jersey

Commanding Officer, Springfield Armory, Springfield 1, Massachusetts
1
SWESP-TX, Research and Development Division

Commanding Officer, Watertown Arsenal, Watertown 72, Massachusetts
1
ATTN: SMLWT-EX, Chief, Engineering Division
1
SMLWT-0E, Industrial Engineering Section

Commanding Officer, Watervliet Arsenal, Watervliet, New York
1
ATTN: SWEVT-RR

Commanding General, U. S. Army Chemical Warfare Laboratories, Army Chemical Center, Maryland
1
ATTN: Technical Library

Commanding Officer, U. S. Army Environmental Health Laboratory, Army Chemical Center, Maryland

Commanding Officer, Engineering Research and Development Laboratory, Ft. Belvoir, Virginia
1
ATTN: Materials Branch

Commanding General, Quartermaster Research and Development Command, Natick, Massachusetts
1
ATTN: AMXRC, Clothing and Organic Materials Division

Headquarters, U. S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey
1
ATTN: Materials Branch

1

1
Commanding Officer, U. S. Army Research Office, (Durham), Box CM, Durham, North Carolina
Chief of Research and Development, U. S. Army Research and Development Liaison Group, APO 757, New York

1
ATTN: Dr. B. Stein

Chief, Bureau of Naval Weapons, Department of the Navy, Room 2225, Munitions Building, Washington 25, D. C.

1
ATTN: RMMP

Chief, Bureau of Ships, Department of the Navy, Washington 25, D.C.

1
ATTN: Code 344

Chief, Office of Naval Research, Department of the Navy, Washington 25, D.C.

1
ATTN: Code 423

Chief, Special Projects Office, Bureau of Naval Weapons, Department of the Navy, Washington 25, D.C.

1
ATTN: SP 271

Commander, U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland

1
ATTN: WM

Commander, U. S. Naval Ordnance Test Station, China Lake, California

1
ATTN: Technical Library Branch

Commander, U. S. Naval Research Laboratory, Anacostia Station, Washington 25, D.C.

1
ATTN: Technical Information Center


1
ATTN: Lt. Col. J. B. Shipp, Jr.

ARDC Flight Test Center, Edwards Air Force Base, California

1
ATTN: Solid Systems Division, FTRSC

AMC Aeronautical Systems Center, Wright-Patterson Air Force Base, Ohio

2
ATTN: Manufacturing and Materials Technology Division, LMBMO

National Aeronautics and Space Administration, 1520 H Street, N.W., Washington 25, D.C.

1
ATTN: Mr. G. C. Deutsch

1
Mr. R. V. Rhode
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California
1
ATTN: Dr. L. Jaffe

George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama
1
ATTN: M-S&M-M
1
M-F&AE-M

Commanding Officer, U. S. Army Materials Research Agency, Watertown 72, Massachusetts
5
ATTN: AMXMR-LXM, Technical Information Section
1
AMXMR-OPT
1
AMXMR, Dr. R. Beeuwkes, Jr.
1
Author

65 -- TOTAL COPIES DISTRIBUTED
A novel ultrasonic test method is described utilizing ultrasonic signals which contain a broad band of frequencies, and, in analogy to optics, can therefore be considered as "white" ultrasonic pulses. The form and spectral energy distribution, or "color", of such ultrasonic pulses is influenced by the geometry of a defect from which they are reflected. Hence, an analysis of the defect echo yields information on the defect configuration.