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ULTRASONIC FREQUENCY ANALYSIS

H. L. Whaley and K. V. Cook

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ORNL-TM-2655

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION

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SEPTEMBER 1969

Paper for 29th National Convention, American Society for Nondestructive Testing, Philadelphia, Pa., October 13–16, 1969. Submitted to Materials Evaluation.

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ABSTRACT

In order to increase our understanding of frequency effects in ultrasonic testing, we have developed a system which can analyze the frequency content of reflected or transmitted ultrasonic pulses. The system is composed of commercially available electronic equipment and can be used with conventional ultrasonic instruments operating in either a contact or immersion mode. We have applied the system to examine the frequency effects of the following ultrasonic test variables: transducer type, ultrasonic instrument type, transducer positioning, tuning devices, and collimation.

INTRODUCTION

In conventional pulsed ultrasonic testing, the amplitude and arrival time of the reflected pulse are the parameters of main interest, yielding information about flaw size and position, respectively. Frequency is considered in the test setup in regard to attenuation in the material, defect size to be detected, and required resolution, but this only allows the operator to select a nominal operating frequency. The detailed frequency dependence of the effects produced by the sample is not generally used to provide information on the characteristics of the sample, except, of course, in thickness gaging.

Gericke[1] has shown that the use of short, untuned pulses to drive an ultrasonic transducer can produce a wide range of frequencies in the

[1]O. R. Gericke, "Determination of the Geometry of Hidden Defects by Ultrasonic Pulse Analysis Testing," J. Acoustical Soc. Am. 35, 364–368 (March 1963).

generated pulse, or in his analogy to optics, a "white" pulse. He has demonstrated that frequency-based (as opposed to amplitude or time-based) information can provide a new tool for ultrasonic testing. In a number of interesting papers[2] he has described the specialized electronic system developed at the U.S. Army Materials Research Agency at Watertown and results obtained with transducers operating in a contact mode.

To investigate some of the promising areas, we have developed an electronic system for analyzing the frequency content of ultrasonic pulses. The system can work with contact transducers, but is better suited and mainly intended for the immersed technique. Some of the reasons we prefer the immersed technique for frequency analysis are that it allows us to use flat, focused, and collimated transducers, to vary transducer-to-specimen spacing and angle of incidence, and it also eliminates the problem of reproducing coupling. Moreover, we ultimately hope to employ frequency analysis in automated testing, which is, of course, usually done by immersed techniques. The components are common commercial instruments, and the system as a whole is well adapted to use with conventional ultrasonic instrumentation. The flexibility of the system allows us to use it for both reflection and through-transmission techniques. Its application has revealed some very interesting and useful information regarding some of the frequency effects of common ultrasonic test variables such as transducer and instrument types, transducer positioning, and the use of tuning and collimating devices.

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[2] O. R. Gericke, "Defect Determination by Ultrasonic Spectroscopy," J. Metals 18(8), 932–937 (1966); "Ultrasonic Spectroscopy of Steel," Mater. Res. Std. 5(1), 23–30 (1965).

DESCRIPTION OF THE ELECTRONIC SYSTEM

Figure 1 is a block diagram of the ultrasonic frequency analysis system. The Appendix is a list of the equipment identifying the manufacturer and model number of each component. The immersion technique is illustrated schematically with a single transducer acting as both pulser and receiver (pulse-echo).

As can be seen, the high-voltage (500–1700 v) pulse that excites the transducer and reflected pulses from the specimen enter preamplifier No. 1. The preamplifier is saturated by the excitation pulse for a few microseconds, but then recovers and amplifies without distortion the

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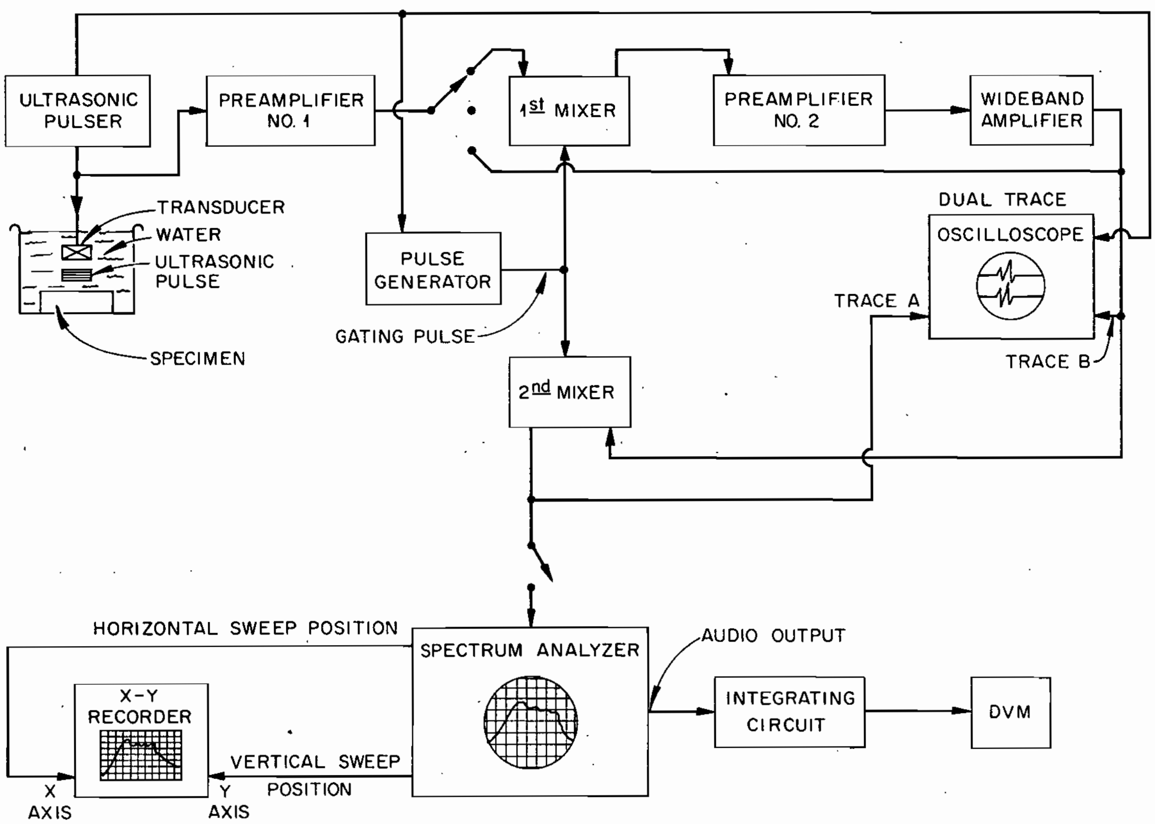

Fig. 1. Block Diagram of the Ultrasonic Frequency Analysis System.

low-voltage signal pulses of interest if a water column of about 0.5 in. or greater is maintained. This much water column is required only if one wants to analyze the first signal to return from the sample (i.e., the reflection from its front surface). From the output of preamplifier No. 1 comes a succession of radio-frequency (rf) pulses resulting from reflections from the front surface of the specimen, multiples of front- and rear-surface reflections, and possibly reflections from internal discontinuities. If the pulse of interest is sufficiently large, the switch following preamplifier No. 1 is put in the lower position, and all these pulses are displayed on the "B" trace of a dual-trace oscilloscope. They are also connected into a solid-state mixer ("second mixer" in Fig. 1) which operates as a pedestal-free gate. The output of a pulse generator synchronized with the ultrasonic pulser is connected to a second input of the mixer. There is an output at the third terminal when the arrival time of this gating pulse coincides with one of the rf pulses. This output is displayed on trace "A" of the oscilloscope so that the signal to be analyzed can be selected by adjusting the timing of the gating pulse.

If additional amplification of the signal pulse is needed, the switch after preamplifier No. 1 can be set to connect the signals through the first mixer to preamplifier No. 2 and a wideband amplifier before going to the second mixer. It was necessary to use a mixer between the preamplifiers for isolation and to screen out larger pulses. The second preamplifier alone produces about a 10× increase in the amplitude of very small signals. At maximum sensitivity, signals can be analyzed which are at least 20 db smaller than those from a 3/64-in.-diam flat-bottomed hole drilled in an aluminum plate (this was observed using a flat, 5-MHz immersion transducer).

The gated signal is applied to a spectrum analyzer which produces on a cathode ray tube (CRT) a display of the relative amplitude as a function of frequency. The frequency range of the instrument is 0–25 MHz, and adjustable center-frequency and bandwidth enable one to examine any portion of a displayed spectrum in detail. Frequency markers may be displayed on the CRT along with the spectrum. A simple circuit integrates the audio output of the analyzer to give a direct current (dc) voltage directly proportional to the area (or average amplitude) under a spectrum envelope, allowing a single number to be attached to a given display. This was done because it is difficult to observe several spectra in succession and evaluate their differences based on the shape of the envelope alone. Such an output would in general be more suitable than a CRT display, if, for example, there were continuous changes in the presentation during scanning. When permanent recordings of the displayed spectrum are desired, an X-Y recorder is used as illustrated in Fig. 1.

Known sources of distortion were eliminated to assure that the characteristic spectral shape of the pulse of interest was not affected by our attempts to observe it. The analyzed pulse is not necessarily identical to that initially transmitted, since it depends not only on the transmitter characteristics of the transducer and the characteristics of the sample but also on the receiver characteristics of the transducer. The reproducibility of the system has been demonstrated so that relative frequency changes can be measured confidently.

FREQUENCY EFFECTS OF SOME ULTRASONIC TEST VARIABLES

We have applied the frequency analysis system to determine the nature of frequency effects in certain variables in ultrasonic testing.

Those chosen were parameters that are present and must be considered in the majority of ultrasonic test setups. Consideration of some of the results points out the need for those of us involved in ultrasonic testing to give greater attention to the frequency domain.

Type of Transducer

The broadbanded response of many of the transducers on the market today when driven by short, untuned pulses is quite unlike the mental picture which may be prompted by reference to a nominal frequency stamped on the case. Instead of a sharply tuned peak at the nominal frequency as one might expect to see, the response may look more like Fig. 2. This is the analysis of the front surface reflection from a large, flat plate of a pulse from a nominal 5-MHz, 0.75-in.-diam, flat, lithium sulfate

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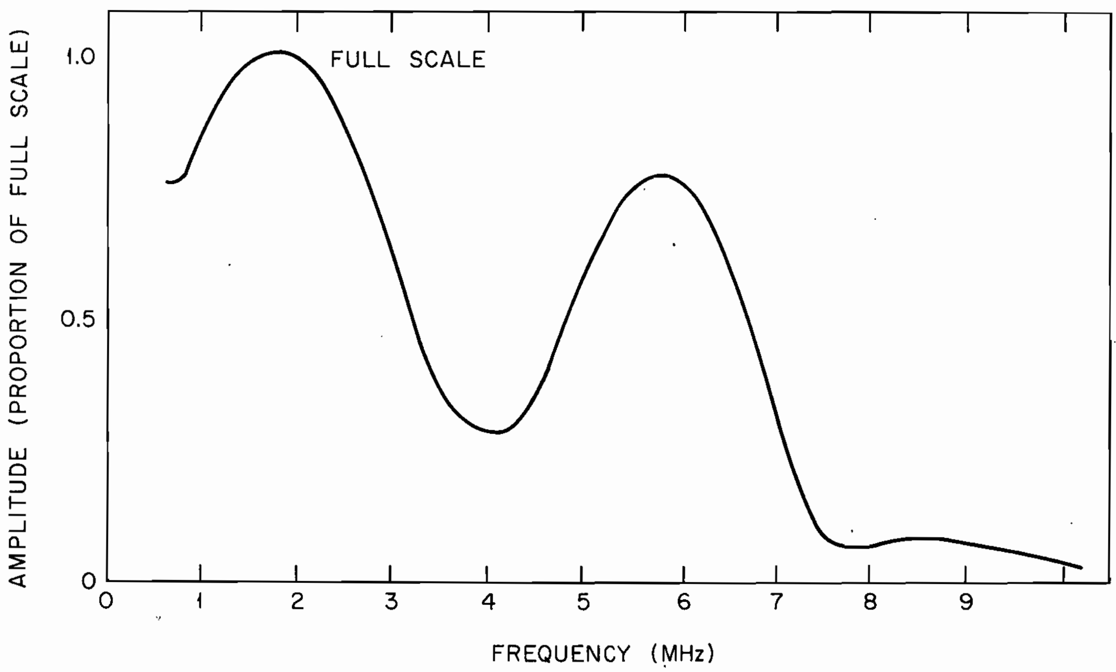

Fig. 2. Analysis of the Spectrum of a Nominal 5-MHz Transducer Excited by a Direct Current Voltage Spike.

transducer that was energized by a negative dc spike. It is interesting to note that the largest peak is near 2 MHz and that the next largest is nearer 6 than 5 MHz. This result does not necessarily imply that this transducer is defective or unfit for testing purposes or that the manufacturer was careless or erroneous in his labeling, but the resultant spectrum can affect the results of an ultrasonic test depending upon such things as the characteristics of the specimen and the bandwidth of the receiver. It must be kept in mind that the shape of the driving pulse has a dramatic effect on the spectrum. This point will be discussed in detail a little later. Most lithium sulfate and ceramic transducers we have checked have produced relatively broadbanded spectra when energized by a dc voltage spike.

Quartz transducers have a very sharply tuned response as shown in Fig. 3, which is a photograph of the display of the spectrum analyzer. The uniformly spaced vertical lines are frequency markers 0.5 MHz apart. The first marker (reading left to right) is at 0.5 MHz, the second at 1 MHz, etc. Thus, a sharply tuned pulse at approximately 2.25 MHz is generated by this quartz transducer, which is labeled 2.25 MHz. There is also a harmonic with a smaller amplitude generated at approximately 6.75 MHz. A logarithmic scale of amplitude was used in order to show the latter peak more clearly.

In order to maximize test sensitivity, a knowledge of the frequency response of the transducer under actual operating conditions is required. For example, assume one is exciting a lithium sulfate transducer with a short dc spike and producing a broadbanded spectrum with pronounced peaks at one or two frequencies. If the receiver he is using is narrowbanded, Photo 88557

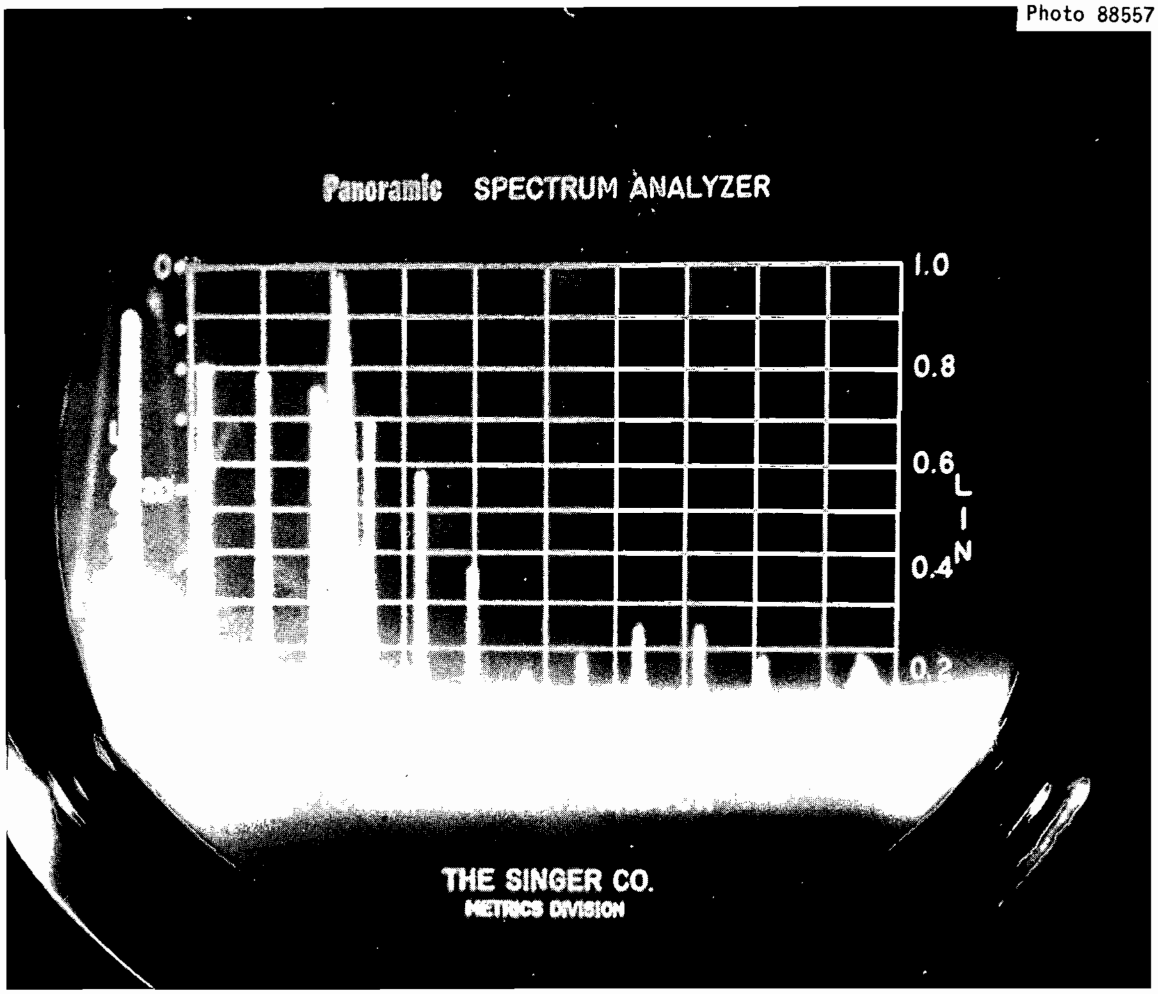

Fig. 3. Spectrum Display of a 2.25-MHz Quartz Transducer with 0.5-MHz Frequency Markers.

it may be tuned to a frequency at which the transducer is producing relatively little energy, resulting in less than maximum sensitivity. If the receiver is very broadbanded, the importance of the positions of maxima and minima may diminish, depending, of course, upon how the exact frequencies influence the inspection. It should be kept in mind that the interpretation of the influence of frequency spectra on ultrasonic test results must always consider the nature of the receiver of the test instrument.

A focused transducer may use either a norrowbanded or broadbanded crystal element. One observed effect of having a broad range of frequencies present is to make the focal point of the transducer somewhat less well defined than would be the case if a narrow frequency band were used. However, if a very narrowbanded receiver is used, the transducer will still appear to have the very well-defined focal point characteristic of of a narrowband pulse.

Type of Ultrasonic Instrument

The two basic methods of pulsing the transducer in ultrasonic testing are: (1) by the use of an untuned fast-rise-time voltage shock; and (2) by a pulse consisting of a few cycles of an rf wave form of adjustable frequency (tuned pulse). We analyzed the spectra generated by five of our basic ultrasonic test instruments. All were commercial instruments in common use.

Three of these (supposedly identical) had untuned pulsers which produced wideband spectra when pulsing the test transducer (lithium sulfate). We noted that the spectra did not depend upon the particular instrument used, but were essentially constant when generated with the same transducer.

The other instruments we used were tuned-pulse instruments which tune the transducer output to the selected operating frequency. Therefore, varying the pulser frequency varies the output frequency and amplitude according to the response of the transducer at various frequencies.

As has been pointed out before, the influence of variations in the frequency spectra of a pulse upon a given test can depend on the type of receiver used in the test instrument. The bandwidths of receivers of modern ultrasonic instruments range from those many megahertz in width to those which are quite sharply tuned.

Transducer Positioning

Angle

We are all aware that the amplitude of a reflection from a flat plate decreases very quickly if the transducer axis is misaligned from normal to the surface. This fact is used to achieve perpendicular alignment during test setups. However, the very large relative loss of higher frequencies is not apparent on an amplitude-sensitive instrument. Figure 4 shows the drastic loss of higher frequencies resulting from a transducer misalignment of only 1° from normal. The transducer was a flat, 3/4-in.-diam, lithium sulfate type. The left-hand portions of the

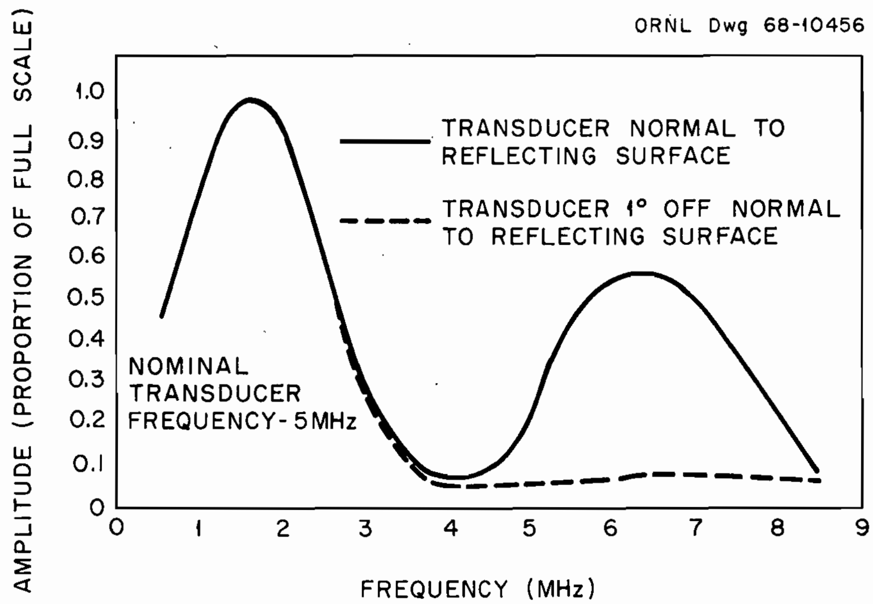

Fig. 4. Frequency Spectra Changes Due to Misalignment of Ultrasonic Beam 1° from Normal.

two curves were normalized for comparison. The effect is explained by the fact that the higher frequencies are more directional. Such a pronounced effect is not seen for a focused transducer since the direction of propagation is not as well defined.

Distance

Figure 5 illustrates the relative acoustic intensity along the transmission axis of a plane, circular element. Both axes have been left dimensionless since the figure is intended to illustrate the general case. The positions on the x axis of the y^+ (maxima) and y^- (minima) points are described by the following equations:[3]

$$y_m^+ = \frac{4a^2 - \lambda^2 (2m + 1)^2}{4\lambda (2m + 1)} , \quad m = 0, 1, 2 \ldots \qquad (1)$$

$$y_m^- = \frac{a^2 - \lambda^2 m^2}{2m\lambda} , \quad m = 1, 2, 3 \ldots \qquad (2)$$

[3]"Ultrasonic Transducers," p. 44.13 in Nondestructive Testing Handbook (Robert C. McMaster, ed.), Vol II, The Ronald Press Company, New York, 1959.

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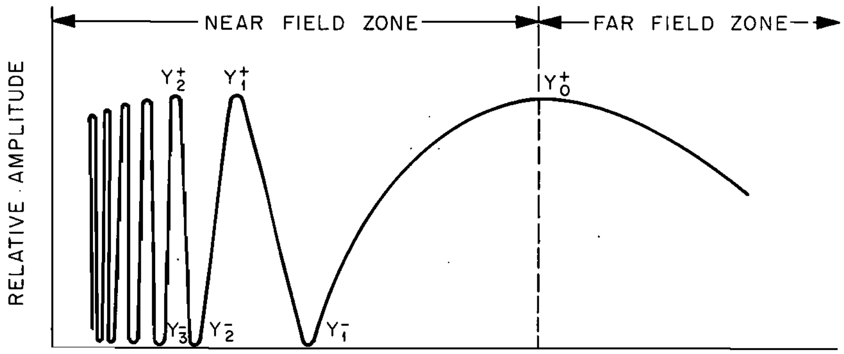


Fig. 5. Axial Acoustic Intensity of a Plane, Circular Source.

where a is the radius of the circular source and λ is the wavelength of sound in the material in which it is propagating. If a broadbanded pulse is generated, each frequency will have its own set of "y points." Thus if it is desired to conduct a test in the near-field zone, the use of a broadbanded pulse and receiver can reduce the criticality of distance to the flaw.

In view of the near-field structure described, one might expect to see significant fluctuations in the spectrum of a pulse reflected from a large, flat surface as transducer-to-reflector distance is varied in the near-field zone.

Figure 6 presents data taken to determine the effect of length of water column on the frequency spectrum of a pulse reflected normally from the surface of a large, flat plate (curves have been normalized). There are no drastic changes but rather a gradual, relative loss of higher frequencies which is due to a variety of factors such as beam divergence, imperfect alignment, attenuation, scattering in the water, and surface roughness of the sample. In this case, the previously described details of the near-field structure are obscured due to the averaging of variations in the off-axis pressure distribution because of the use of a large reflecting surface.

Tuning Devices

Various tuning devices are often employed in the transducer circuit of an ultrasonic test system in an attempt to improve sensitivity. These tuning devices affect the impedance of the circuit, the shape of the excitation pulse, and thus the frequency spectrum of the transducer.

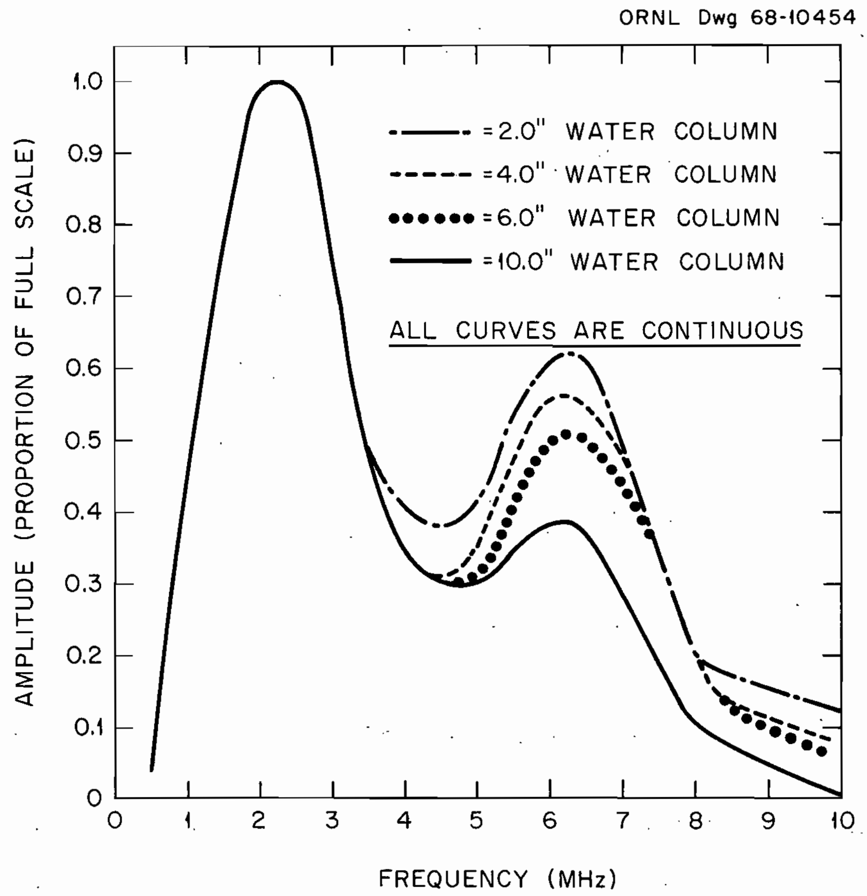


Fig. 6. Frequency Spectra Changes Due to Increasing Water Distance Between Ultrasonic Transducer and Specimen.

Since these effects can be quite complicated, we employed the frequency analysis technique to observe the frequency response of the integrated system as a function of tuning.

One type of tuning network investigated consisted of a number of rf coils, each with a resistor in parallel. An rf coil-resistor pair is selected by a rotary switch. The unit is commonly mounted on the transducer search tube for ease of operation. Figure 7 shows an analysis of the frequency content of the electrical excitation pulse and the corresponding reflected ultrasonic pulse in the bypass (no tuning) position and the positions labeled 5 and 10 MHz on the tuning box. A broadbanded

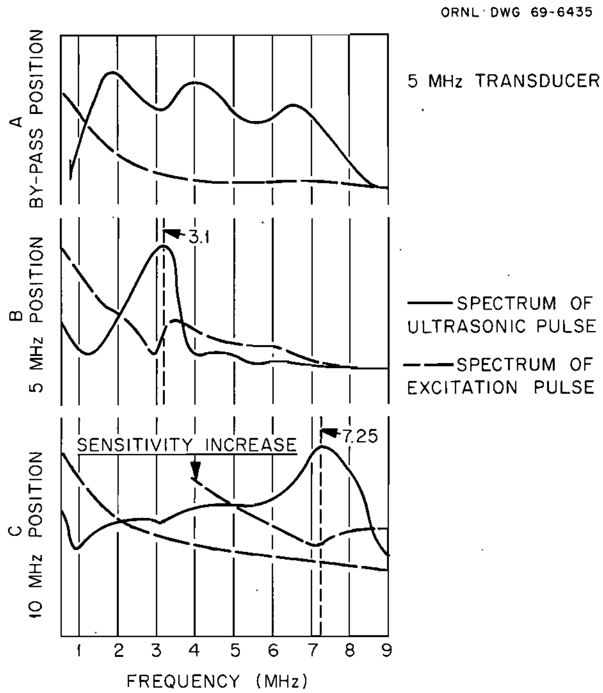


Fig. 7. Transducer Frequency Response with Inductor-Resistor Tuning.

5-MHz lithium sulfate transducer was used [Fig. 7(a)]. The largest peak in each spectrum was adjusted to full scale, and a logarithmic vertical scale was used.

In the 5-MHz position [Fig. 7(b)] a dip occurs in the spectrum of the excitation pulse near the principal energy peak in the spectrum of the ultrasonic pulse. A similar situation occurred in the 10-MHz position [Fig. 7(c)], but in order to make the dip visible, the sensitivity had to be increased around 7 MHz for the analysis of the excitation pulse.

This type of network narrows the response of the transducer somewhat, but does not necessarily optimize the response at the desired frequency without adjustment. Core slugs in the tuning coils allow some adjustment of the position of the peaks in the ultrasonic pulse, but it is likely that impedance differences between various kinds of transducers of the same nominal operating frequency would require custom tuning.

If harmonics of the principal frequencies in Fig. 7(b) and (c) were present, they were very small relative to the principal frequencies and lost in the noise.

A second type of tuning device described by its manufacturer as a "tunable peaking coil" produced a much more narrowbanded spectrum with well-defined harmonics of the principal frequency. Figure 8(a) is a graph of the analysis of pulses from a 2.25-MHz, flat transducer with normalized curves showing response without and with a peaking coil rated at 2.25 MHz. Figure 8(b) is on a vertical log scale so that the harmonics present with the peaking coil can be shown.

In some cases, tuning devices such as the tunable rf coils discussed here increase the transducer output at or near the nominal frequency

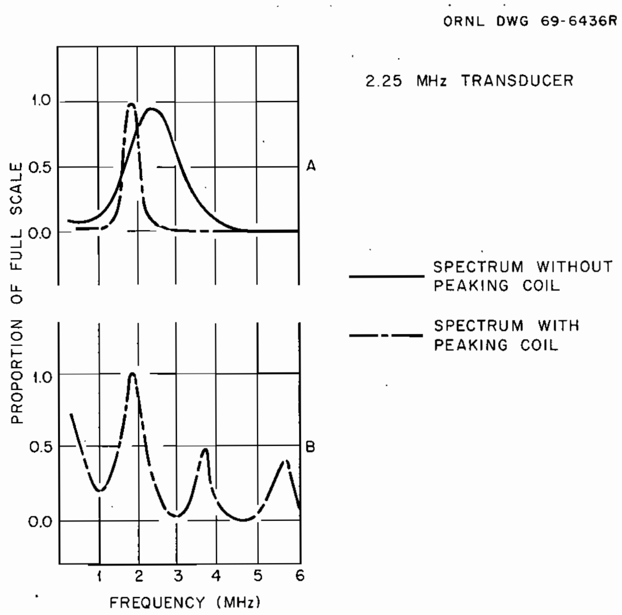


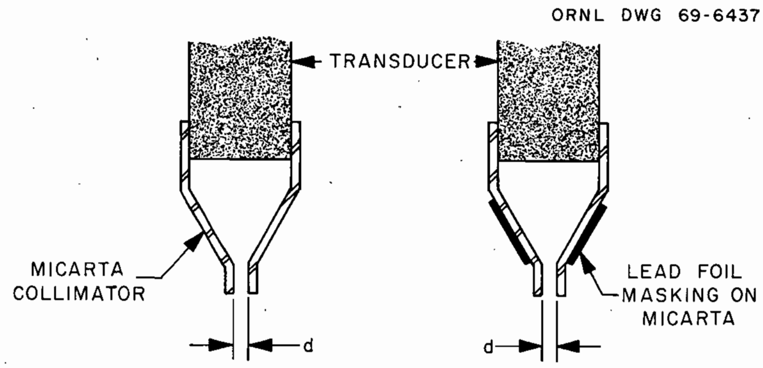
Fig. 8. Transducer Frequency Dependence on "Peaking" Coil. (A) Spectra With and Without Peaking Coil Using the Linear Amplitude Response of the Analyzer. (B) Spectrum With the Peaking Coil Using the Logarithmic Amplitude Response of the Analyzer.

while in other cases they actually cause less output at the desired frequency and thus less sensitivity or use of unexpected frequencies in a test setup.

Collimation of Ultrasonic Beam

Collimating devices are attached to ultrasonic transducers to limit the beam diameter and thus increase sensitivity to smaller flaws. These devices are made from a variety of materials and in a variety of shapes. They are basically an aperture of chosen size and shape in a material relatively opaque to sound at ultrasonic frequencies. To a fair approximation, an ultrasonic beam passing through a collimator assumes a cross section with the same size and shape as the aperture.

The frequency analysis system was applied to see whether or not there are changes in the frequency spectrum as a result of diminishing size of the aperture. For this test five collimators, shaped as shown in vertical cross section in Fig. 9, were employed. A 2.25-MHz, flat, 3/4-in.-diam transducer was used with each of the collimators. The front-surface signal from a large, flat plate whose surface was normal to the transducer axis was analyzed for the uncollimated transducer and for each collimator illustrated in Fig. 9. The results appear in Fig. 10. A shift in the principal energy peak toward lower frequencies was observed for the 1/8- and 1/16-in. unmasked collimators. However, these collimators were found to be "leaking" (i.e., appreciable energy was being transmitted through the wall of the collimator near the tip). When collimators of these two sizes with lead-masked walls were tried, the peak shifted back to the uncollimated position for the 1/8-in. aperture, and



TYPE COLLIMATOR	APERTURE DIAMETERS (d, in.) USED
UNMASKED	1/16, 1/8, 3/8
MASKED	1/16, 1/8

Fig. 9. Types and Sizes of Collimators Studied for Determination of Effect of Aperture Size on Frequency Spectra.

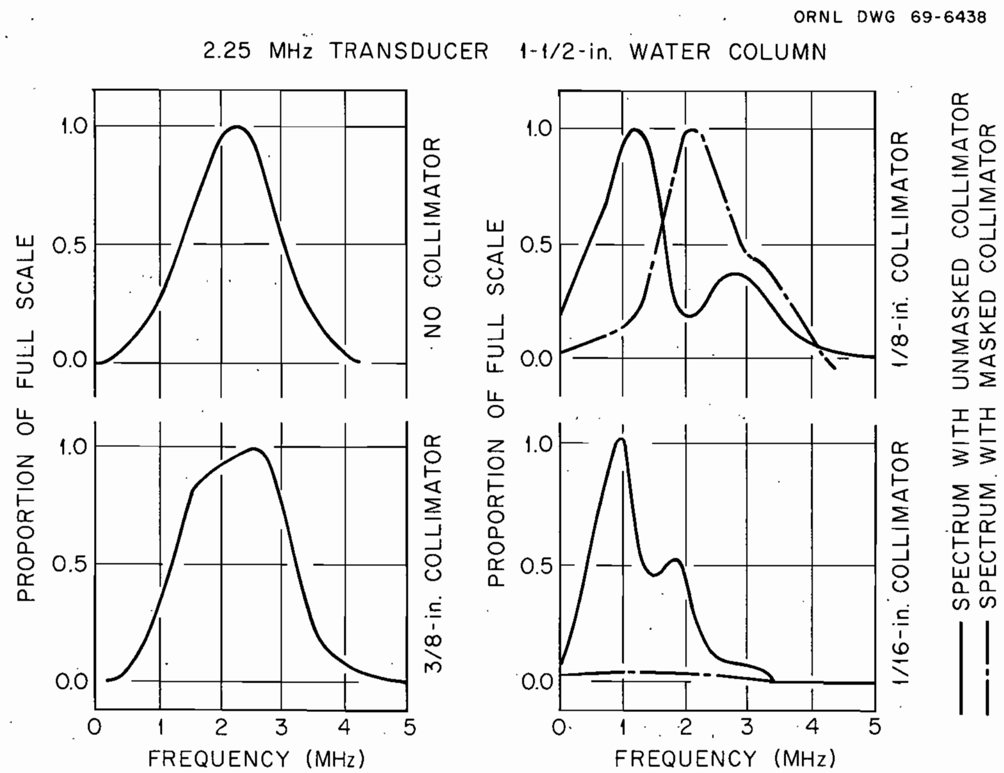


Fig. 10. Spectral Analysis of Pulses from a Collimated Transducer Showing a Frequency Shift Due to Leakage.

sufficient energy was not available to perform an analysis for the 1/16-in. aperture. This latter fact indicates that the energy analyzed in the case of the 1/16-in.-diam unmasked collimator came from leakage. The leakage becomes more important with smaller collimator apertures because amplification must be increased to detect the narrow beam. The lower frequencies predominate in the leakage energy because they are attenuated less in the collimator material and are less directional than higher frequencies. Leakage probably occurs to some extent with most collimators. This can result in an effective beam diameter larger than desired and thus less sensitivity to the smaller flaws. The effective shift to lower operating frequencies could also impair test sensitivity.

Undoubtedly, a direct frequency effect due to collimation would be present for aperture sizes approaching the wavelength of the sound in the water where diffraction effects would begin to be more important.

CONCLUSIONS

A system has been developed for analysis of the frequency spectra of selected ultrasonic pulses. The system uses commercially available equipment and operates in all the modes commonly used in ultrasonic testing. Thus, it may be used as an independent research tool or perhaps applied in conjunction with conventional test techniques to yield supplementary information. Application of the system to study frequency effects of some of the common ultrasonic test parameters has yielded interesting and useful information which should be considered in making ultrasonic tests.

There are many potentially productive areas in which frequency analysis may be applied in ultrasonics. One area that we are now studying is that of the influence of flaw size and orientation on the frequency spectrum. A second area in which we have demonstrated feasibility is the determination of bond quality by frequency analysis.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to B. W. Castleman (graduate student, Florida State University) for his valuable contributions in the earlier stages of this work. They also wish to thank R. W. McClung, Group Leader, Nondestructive Testing Development, for his continuing advice and recommendations throughout the program.

APPENDIX

APPENDIX

Identification of the Equipment

Designation in Fig. 1	Manufacturer	Model
Ultrasonic pulser	May be any one of several makes and types	
Preamplifier No. 1	Tektronix	Type L
Preamplifier No. 2	Tektronix	Type 53-B
Mixers	Anzac Electronics	ASM-10
Wideband amplifier	Hewlett-Packard	460 AR
Pulse generator	Hewlett-Packard	214-A
Oscilloscope	Tektronix	545 (with 53/54 C plug-in)
Spectrum analyzer	Singer Company, Metrics Division	Spa-3/25a
Digital voltmeter	Fairchild	7050
X-Y recorder	Moseley	7000A

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