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COMPUTER SIGNAL PROCESSING FOR ULTRASONIC ATTENUATION AND VELOCITY MEASUREMENTS FOR MATERIAL PROPERTY CHARACTERIZATIONS

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Abstract

This report deals with instrumentation and computer programming concepts that have been developed for ultrasonic materials characterization. Methods that facilitate velocity and attenuation measurements are described. The apparatus described is based on a broadband, buffered contact probe using a pulse-echo approach for simultaneously measuring velocity and attenuation. Instrumentation, specimen condition, and signal acquisition and acceptance criteria are discussed. Typical results with some representative materials are presented.

1. INTRODUCTION

1.1 BACKGROUND

There is high interest in the potential uses of ultrasonics for nondestructive characterization of materials. Physical bases and a rationale for quantitative ultrasonic evaluation of mechanical properties of materials were recently reviewed (1). It was noted that even where conventional nondestructive evaluation, NDE, techniques have shown that a part is free of overt defects, advanced NDE techniques should be available to confirm critical material properties assumed in the part's design.

Among the available NDE techniques (including radiometry, eddy currents, microwaves, etc.) ultrasonics is now prominent as a highly versatile means for mechanical property characterization. Mechanical properties that can be ultrasonically evaluated include elastic moduli, tensile strength, yield strength, ductility, hardness, and fracture toughness.

Ultrasonic measurements of mechanical properties depend on making accurate and precise velocity and/or attenuation measurements. Examples where both kinds of measurements are used include determination of hardness and tensile strength (1) and correlations of yield strength and fracture toughness (2).

1.2 ORGANIZATION

This report describes instrumentation and programming concepts that facilitate velocity and attenuation measurements in ultrasonic NDE of material properties. Practical factors essential to making ultrasonic measurements for quantitative material property characterization are discussed. Operational details are given as a guide for further system and instrumentation developments.

The waveform aquisition and processing concepts described generally relate to laboratory material samples. However, the instrumentation and programming guidelines are applicable to a variety of actual structural parts if specified size, geometry, surface quality, and morphological conditions are satisfied.

This report has four major sections: INSTRUMENTATION, SIGNAL ACQUISITION, SIGNAL PROCESSING, and REPRESENTATIVE RESULTS.

2. INSTRUMENTATION

2.1 OVERALL SYSTEM

An ultrasonic waveform processing system based on a high frequency digitizer and high speed minicomputer was assembled from commercially available components. At this writing, the system appears to be unique in its capabilities for performing high frequency ultrasonic signal analyses.

A contact probe, multiple pulse echo approach is used for the velocity and attenuation measurements. Simplicity of application and versatility are afforded in combining both the pulse emitter and signal receiver in a single ultrasonic probe that requires access to only one surface of a sample material. The signal acquisition and processing arrangement is shown in figs. 1 to 3. The principal system components are:

(1) Buffered ultrasonic transducer
(2) Broadband pulser-receiver
(3) Programmable waveform digitizer
(4) Interactive graphics terminal
(5) Minicomputer and software system

The above major components and pertinent operational factors are described below.

2.2 ULTRASONIC TRANSDUCER

It is advantageous to use a buffered, broadband ultrasonic transducer such as that illustrated in fig. 1. The buffer isolates the transducer crystal from the specimen and eliminates adverse loading effects that can disturb and distort incoming signals.

A single 50 MHz transducer is the basis for data reported herein. It contains a ceramic piezoelectric element polarized to emit longitudinal waves. The buffer is a fused quartz circular solid cylinder with polished ends. The buffer length is 12.7 mm (0.5 in) giving a buffer delay fixed at 4.3 microseconds. The buffer diameter is 16 mm (.63 in) and the piezoelectric crystal has a 6.3 mm (.25 in) diameter.

2.3 PULSER-RECEIVER

The ultrasonic pulser- receiver is a special manufacturer- modified unit. The modifications consist mainly of a sharpened excitation pulse and extended high frequency drive in order to achieve greater amplification and wider bandpass performance. The receiver amplifier has a 75 MHz bandpass. The excitation pulse has a 200 volt peak, 3 nanosecond risetime, and 10 nanosecond duration. These are minimum values that can be increased by an energy control dial. The instrument also includes a damping control for impedance matching the transducer with the pulser- receiver and an attenuation control for reducing the effects of distortion in the amplifier circuit.

2.4 WAVEFORM DIGITIZER

Waveform acquisition for ultrasonic velocity and attenuation measurements is accomplished by means of a high frequency waveform digitizer in which analog time domain signals are converted into digital arrays. The waveform digitizer is a state-of-art controller-based instrument with a silicon diode scan converter matrix.

High gain and bandwidth are achieved by signal capture on the diode target matrix. Signal capture is done at high speed while subsequent digitization proceeds more slowly at computer compatible data transfer rates. Signals containing frequencies from 10 Hz to 1 GHz are readily digitized by the scan converter.

Signal and synchronization inputs to the digitizer are made through modular oscilloscope plug-ins consisting of a dual channel vertical amplifier and a time base with delayed and delaying sweep provisions. The vertical module operates at a 300 MHz bandwidth, The time base has a sweep rate of 500 picoseconds per division. This allows signal capture within a 5 nanosecond time frame. An x-y video oscilloscope monitor is used to view signals in real-time as they are written on the diode target matrix.

The digitizer produces 512 element waveform arrays. After scan conversion, raw waveform arrays are retrieved under program control from a self contained (4096-word) memory. Each of the 512 waveform array elements is associated with a horizontal time value and vertical voltage deflection representing the time domain signal.

2.5 GRAPHICS TERMINAL

In addition to the usual programming and data display operations, the graphics terminal is a vital link for interactive signal processing. Raw or processed waveforms, program generated graphics, and other data displays are called up by direct operator intervention or under program control. This enables operator interaction with intermediate as well as final results, when necessary.

The system includes a hard copy unit for reproducing program listings, data, and graphics from the terminal screen. Documents are deliverable at about 10 second intervals. Example of figures produced by the graphics package appear throughout this report.

2.6 CONTROLLER AND SOFTWARE

The controller consists of a high-speed minicomputer with a 64,000 word memory serviced by two 1.2 million word disks. The controller has a real-time operating system, memory management, universal bootstrap, automatic self diagnotics, and floating point processor. Of the 64,000 word memory, about 20,000 words are occupied by the operating system, about 12,000 words are reserved for programs and processing, and the remaining 32,000 words are available as "virtual" memory for expanded high speed data and array processing.

The computer resident software system incorporates a high level language (modified BASIC) (3) specifically evolved for the waveform digitizer by the manufacturer's software development group. The software includes modules for instrument control, peripheral support, graphics, waveform and array processing. The waveform and array processing modules include subroutines for convolution, cross correlation, auto correlation, signal mean, maximum and minimum, zero cross, root mean square, differentiation, integration, and "fast" Fourier transforms "FFT" (4).

3. SIGNAL ACQUISTION

3.1 GENERAL CONDITIONS

This section describes factors that govern the acquisition of viable signals. Guidelines are suggested for material preparation and probe coupling. In addition, procedures for signal adjustment, definition, and acceptance relative to making accurate attenuation and velocity measurements are provided.

The signal definition and acceptance criteria are predicated on materials that are linear elastic, nondispersive, and essentially isotropic. Materials are assumed to have a uniform, polycrystalline, fine grained microstructure with the mean grain size being much less than the mean wavelength of the probe signal. This assures operation in the scatter attenuation regime which is assumed for the attenuation coefficient measurements described herein.

3.2 MATERIAL SAMPLE

To accomplish the quantitative attenuation and velocity measurements needed to measure material properties ultrasonically, the material sample must satisfy some specific size, shape, and surface quality constraints. Acquisition of optimal signals requires:

(1) Clean, machine-finished surfaces
(2) Flat, smooth, parallel surfaces
(3) Precisely machined thicknesses
(4) Large area relative to probe size
(5) No internal defects or anomalies

Flat, ground or machined surfaces assure good probe coupling. For absolute velocity and attenuation measurements ultrasound pulses should be introduced at normal incidence. Signal transmission should be between parallel surfaces. These constraints reduce the deleterious effects of beam divergence and other geometry related factors.

The distance between the parallel surfaces used in multiple pulse echo measurements should be precise and relatively small. If the material thickness is too great, attenuation losses will tend to diminish the chance of recovering strong echoes, B1 and B2. Conversely, material sample thickness should be great enough to give a good basis for velocity computations and to include a fair sampling of microstructure.

The region to be probed should be large relative to the probe beam diameter and free of facets or boundaries that will cause extraneous reflections. The region being probed should also have an ample area to permit probe shifting to alternative positions to get good lateral sampling of the material.

Obviously, other NDE methods should be used to verify the assumed absence of overt defects, internal anomalies, or material gradients that might make the sample unrepresentative of virgin material.

[Specimens with plane parallel surfaces with smooth finishes have been used. Surface roughness was less than 16 rms. The specimen surfaces were machine ground and subsequently polished with 600 and 800 grit sandpaper. Typically, the lateral area was from 2 to 4 square cm.]

3.3 BUFFER MEDIUM

The buffer diameter should as a rule be roughly two to three times that of the crystal to avoid sidewall reflections.

The length should be such that at least two back surface echoes from the specimen, B1 and B2, may be readily included between successive buffer echoes, F1 and F2, as in fig. 2. If this condition is met, it is easier to identify and isolate echoes B1 and B2. Otherwise, these echoes can become confused with or run into other multiple echoes in the time domain.

Fused silica and quartz are equally appropriate buffer materials. These materials have a vitreous, amorphous microstructure with very low attenuation in the frequency range of interest. Also, the acoustic impedance of either fused silica or quartz is appropriate for the materials studied. The buffer acoustic impedance should be less than that of the material to which it is coupled. These factors assure ample signal amplitude for the echoes returned by the material, B1 and B2, in fig. 2.

[The buffer in the 50 MHz transducer was fused quartz. The buffer is usually an integral part of commercial probes and its length is fixed by transducer design requirements. Therefore, the specimen thickness was coordinated with buffer length to assure two material echoes in the buffer delay interval. For example, for the materials studied the specimen thickness ranged from 2 to 3 mm.]

3.4 COUPLING MEDIUM

Coupling media such as glycerine, light oils or commercial gel couplants will perform well if the previously noted material surface conditions are met. The couplant should readily wet the material surface.

The couplant thickness should be a minimum and highly uniform. Otherwise, multiple reflections and interference effects within the couplant tend to degrade any high frequency signal components being transmitted. This is a serious undesirable effect in the case of attenuation measurements that rely on spectrum analysis of high frequency signals. The couplant thickness should be reduced to a minimum by squishing. The application of appreciable pressure is needed for this.

[For the glycerine couplant used in this study a squishing force of from 44 to 88 N (10 to 20 lbs) was found appropriate. This was equivalent to from 220 to 440 kPa (30 to 60 psi). Specimens were supported atop an instrumented load cell for these measurements.]

3.5 PULSER-RECEIVER ADJUSTMENTS

As with all instruments of this type, impedance matching of the pulser-receiver circuitry and transducer is a vital factor. The interconnecting cable's length and impedance should be selected to produce optimum signals. To further optimize performance of the transducer- instrument combination, fine control of impedance matching is afforded by a damping control in the cable circuit. Under proper conditions this control will reduce or virtually eliminate "ringing" or reverberations by altering impedance loading between the transducer and pulser- receiver.

Although the resultant signal may be weaker, it is preferable to use minimum pulse energies and hence lower pulse widths with high frequency transducers to get the greatest possible bandwidths. A pulse energy triming control in the pulser circuit should be available for this adjustment.

An attenuation adjustment in the receiver amplifier circuit should be increased as required to reduce signal distortions. These may arise due to amplification nonlinearities. It may be necessary to reduce signal strength of echoes B1 and B2 while attempting to optimize the waveform.

3.6 SIGNAL RESOLUTION

To optimize the digital version of the time domain waveform, back echoes B1 and B2 should be separately digitized into their corresponding arrays. Figure 4(a) shows a composite waveform sythesized into a 1500 element array from the two separate 512 element arrays in figs. 4(b) and 4(c). The purpose of the composite waveform is solely to illustrate the relatively long time delay between successive echoes, B1 and B2. That is, the delay between echoes is very long relative to the duration of oscillations. This is typical for high frequency signals in the material samples studied.

Any digitization of ultrasonic signals that compresses two echoes into a 512 element array will greatly reduce fine structure definition of the waveform of either echo. It is desirable to reduce the data sampling interval to the lowest possible value for each echo to be sampled. Accordingly, the echo waveform should "fill the screen" (i.e., scan converter matrix) in order to get the best signal resolution.

[Typically, the time domain digital sampling interval was from 2 to 0.4 ns (between adjacent time points of the waveform array). This required sweep rates of from 1000 ns to 200 ns per waveform.]

3.7 SIGNAL ACCEPTANCE

A programmed pattern recognition routine or simple visual inspection should be used to reject unacceptable waveforms. Preliminary critical examination of the signals should be done each time the probe is recoupled to the material sample.

Certainly, the signals should be free of random spikes or any significant noise. The time and frequency domains of an ideal waveform is illustrated in fig. 5(a). Acceptable waveforms are shown in figs. 5(b) and 5(c). Unacceptable waveforms appear in figs. 5(d) through 5(f).

Within the time domain, an acceptable waveform is fairly symmetrical and has a "W" shape. The two successive negative oscillations should have nearly equal minima. In the polar version of the frequency domain, the waveform spectrum should exhibit a nearly Gaussian shape. The spectrum should exhibit no prominent multiple peaks, valleys, or distortions.

Acceptable waveforms will occur if the previously mentioned conditions and specimen constraints are satisfied. Unacceptable or much less than ideal waveforms may occur because of:

(1) Defective probe/crystal/buffer
(2) Poor impedance matching
(3) Ringing, underdamping
(4) Poor/nonuniform coupling
(5) Amplification nonlinearities
(6) Scan converter nonlinearities
(7) Material anomalies/defects

Generally, waveform problems are easily remedied by instrumentation adjustments and better sample preparation and higher coupling forces. Good signals will tend to "pop in" and stabilize when optimum coupling is achieved.

4. SIGNAL PROCESSING

4.1 OBJECTIVE

In many instances either velocity or attenuation measurements alone suffice for evaluating material properties. However, both measurements are necessary to evaluate fracture toughness and yield strength (5). In this case velocity measurements are needed to determine acoustic impedances and to augment attenuation measurements from which attenuation coefficients are found. The variation of the attenuation coefficient as a function of ultrasonic frequency is the basis for deducing material fracture toughness and yield strength.

The object, therefore, is to illustrate programmed waveform processing for velocity and attenuation measurements leading to fracture toughness and yield strength correlations. Digital signal processing procedures given herein are based in part on the analog procedures described in ref. 2.

4.2 INITIALIZATION AND INTERACTION

Although the waveform acquisition and analysis are performed under computer control, certain operator actions are required to start and oversee the data processing. The establishment of probe coupling, for example, is done manually. Data concerning the particular material samples being probed are input manually at the terminal keyboard. As the signal processing proceeds, the operator is prompted for various additional inputs. Operator inputs include:

(1) Specimen identification
(2) Thickness and density
(3) Average grain size
(4) Coupling medium
(5) Transducer specifications
(6) Instrument settings
(7) Probe position information
(8) Signal acquisition options
(9) Signal processing options

Specimen data includes a serial number and material or alloy identity. It also includes any available previous property measurements such as hardness, yield strength, toughness, etc.

Previously determined material sample density and thickness values are input at the initialization stage. An ASTM Stardard grain size determined for each material sample is also input. However, this can be circumvented for materials for which a relation between velocity and mean grain size has been previously established (5). In this case, an expression for the functional relation between velocity and mean grain size may be loaded into the program and the grain sized is computed from the velocity measurements.

Transducer specifications include: the nominal (center) frequency, wave mode (transverse or longitudinal), buffer material. Given the buffer material, the program assigns an appropriate acoustic impedance value for use in computing reflection coefficients. The acoustic impedance of the couplant is also determined from previously stored data.

Key pulser- receiver settings and other nonprogrammable instrument settings are input for documentation purposes. Probe positioning information is requested by the program when: (a) the probe is repositioned, or (b) the probe is kept stationary for signal averaging. This enables repetitive sampling at a given position or multiposition sampling. The program will return a tabulation of individual position and averaged data values. These data include velocity and attenuation parameters that can be correlated with material properties, as explained under REPRESENTATIVE RESULTS.

Upon startup, the operator makes preliminary judgements of acceptability from the real-time signals displayed on the x-y monitor. As the waveform processing progresses, the operator may exercise further options based on program generated graphics and data. The options include a selection of alternatives from a repertoire of auxiliary signal processing routines.

4.3 VELOCITY MEASUREMENT

Velocity is calculated from a simulated "pulse overlap" routine in which corresponding parts of the successive echoes, B1 and B2, are compared and matched. Using the previously input material thickness, velocity is computed from the mean time delay between the echoes.

The method of pulse echo overlap for an analog system is described in refs. 2,6. In an analog system two succesive material echoes are manually overlapped on a dual display oscilloscope screen. The time delay required to bring key parts of the two echoes into coincidence is the basis for computing velocity.

The overlapping and velocity computation are performed automatically by the waveform processing system using digital waveform and array processing routines. Array processing routines find specific time elements associated with criterion points of the waveform. Criterion points include the peak values of the first and second major oscillation and the zero crossing point between them. The criterion points are located by an array search process. The mean time delay between successive echoes, B1 and B2, is found by determining the time delay between corresponding criterion points. This is accomplished by reference to a continuous pulse train, as described next.

4.4 REFERENCE PULSE TRAIN

A precision, pulse generator is used to produce a continuous pulse train that alternates with the ultrasonic signals on the x-y monitor and scan converter matrix, see fig. 6. The ultrasonic signal is fed to Channel 1 while the pulse train is fed to Channel 2 of the dual trace vertical amplifier.

Since high signal resolution demands that only one ultrasonic echo at a time be digitized, the reference pulse train is a necessary link between the echoes. The pulse train serves as a time marker by means of which any arbitrary delay adjustment needed to bring either B1 or B2 into the (scan converter) screen area may be determined. The pulse period and phase are adjusted so that a specific pulse "X" will appear with B1 in its time frame, while a specific successive pulse "Y" will appear with B2 in its time frame.

The pulse train period is read into the waveform processing program. Once the two succesive echoes have each in turn been positioned on the (scan converter) screen by the time base delay control, the delay is computed from,

$$(TD) = (TP) - (TX) + (TY)$$

where, (TD) is the time delay required to overlap the echoes, (TP) is the pulse train period, (TX) is the signed time interval between pulse "X" and the mean criterion point of B1, and (TY) is the signed time interval between pulse "Y" and the mean criterion point of B2. The algebraic signs of (TX) and (TY) are positive when their corresponding pulses, X and Y, respectively, lead the echoes and negative if they lag. This is is illustrated in fig. 6. The program then computes velocity (VL) based on the delay from,

$$(VL) = 2(ST)/(TD)$$

where, (ST) is sample thickness.

[Throughout this report the upper case letters enclosed within parentheses represent symbols that always denote specific quantities: frequency (F), reflection coefficient (RC), attenuation coefficient (ALPHA), slope parameter number 1 (BETA1), and so forth.]

4.5 ATTENUATION MEASUREMENT

While velocity remains fairly constant relative to frequency (usually varying less than one percent) over a wide range of frequencies, attenuation will generally vary by several orders of magnitude for the same frequency range. Frequency spectrum analysis is the basis for determining the variation of attenuation as a function of frequency. The frequency spectrum analysis method for an analog system is described in refs. 2,6.

The objective is to find attenuation coefficient (ALPHA) as a function of frequency using the equation,

$$(\mathrm{ALPHA}) = \{\mathrm{LOGN}[\,(\mathrm{RC})/(\mathrm{BB})\,]\} \,/\, [\,2(\mathrm{ST})\,]$$

where, (RC) is reflection coefficient, (BB) is the amplitude ratio B2/B1 at specific frequencies over a range of frequencies, and LOGN denotes natural logarithm. Both (BB) and (ALPHA) are, of course, functions of frequency while (RC) is essentially independent of frequency. The above equation applies only if the opposite side of the material sample is free, that is, exposed to a gaseous medium like air.

To find (ALPHA) as a function of frequency (F), it is first necessary to determine (RC) and a functional relation between (BB) and (F). This is done by means of frequency spectrum analysis and the amplitude ratio curve, ARC, as described next.

4.6 FREQUENCY SPECTRUM ANALYSIS

The ultrasonic frequency spectra are obtained by the discrete fast Fourier transformation, FFT, of time domain signals. Echoes B1 and B2 are individually analyzed into frequency domain arrays. These arrays yield the raw amplitude ratios B1/B2 over a range of frequencies of interest. The ratios are computed at 1 MHz intervals from 0 to 100 MHz.

The FFT is performed on two versions of each of the echo waveforms. First, the FFT's of the natural waveforms of B1 and B2 are created. Second, the FFT is performed on truncated versions of B1 and B2. The truncation consists of setting minor trailing oscillations in the waveform arrays equal to zero. Thus, in the truncated version only the first five major oscillations of the classic "W" pattern are retained. The natural and truncated versions of the signal are congruent except for the excluded tail oscillations.

In the frequency domain, the amplitude spectra of the normal and trucated versions are approximately congruent, if the original signals meet the acceptance criteria given previously. This is illustrated in fig. 7(a) where the solid curves are for the natural waveforms and the dotted curves are for the truncated versions of B1 and B2, respectively.

Not all the frequency domain data is usable. A zoning procedure is required to define a frequency range from which valid attenuation data may be extracted. Zone limits are set by means of the first and second derivatives of the frequency spectrum of the weakest echo, B2. The differentiation is performed on the truncated version since it gives more definitive results.

The maximum of the first derivative, fig. 7(b), defines the lower frequency limit of the zone. This maximum occurs below the center frequency of B2. The second peak of the second derivative defines the zone high limit. This peak occurs above the center frequency of B2. Zone limits defined in this way are indicated by vertical marks. It is seen that the limits correspond to critical infelctions in the spectra.

4.7 AMPLITUDE RATIO CURVE, ARC

The data points in fig. 8 are a plot of spectral amplitude raw ratios B2/B1 versus frequency. The solid curve fitted to the raw data is the amplitude ratio curve, ARC. The ARC represents the functional relation between (BB) and (F). It is evident that the ARC is fitted to only the zoned portion of the raw data. The vertical markers indicate the valid zone defined according to the previous criteria.

Excluded raw data to the left of the valid zone are within the diffraction regime (7). This regime typically extends to about 15 or 20 MHz. It is possible to adjust the raw data by means of diffraction corrections. However, the need for any diffraction corrections is avoided by having abundant higher frequency data (8).

External raw data to the right of the valid zone are discarded chiefly because they fall outside the effective bandwidth sensitivity range of the instrumentation (that is, the pulser-receiver- probe combination).

Using only the raw data from the valid zone, a functional relation between (BB) and (F) is found by an iterative multiple regression routine. This involves three key parameters: the coefficient (C), the exponent (M), and reflection coefficient (RC) in,

$$\{\mathrm{LOGN}[\,(\mathrm{RC})/(\mathrm{BB})\,]\} \,/\, [\,2(\mathrm{ST})\,] = (\mathrm{C})(\mathrm{F})^{(\mathrm{M})}$$

The previous equation is based on the relation between attenuation coefficient (ALPHA) and frequency (F) given by,

$$(ALPHA) = (C)(F)^{(M)}$$

This expression for (ALPHA) is valid under the conditions that scatter attenuation predominates and that (C) and (M) can be taken as constants over the frequency range of interest (5). These conditions apply under the material constraints stated in GENERAL CONDITIONS.

4.8 REFLECTION COEFFICIENT

The key to fitting an ARC to the zoned data depends on finding the reflection coefficient (RC) for the buffer- sample interface. Because of variations in the degree of coupling, the reflection coefficient (RC) is not a fixed or known quantity. If the buffer and material sample interfaced perfectly, as under very high pressure with no intervening couplant, the reflection coefficient would be,

$$(RCB) = [\,(ZS)-(ZB)\,] \,/\, [\,(ZS)+(ZB)\,]$$

where, (ZS) is the sample material acoustic impedance and (ZB) is the buffer acoustic impedance.

When a coupling medium is introduced to get acoutic continuity, (RC) will differ from (RCB). Generally, $(RC) \geq (RCB)$, given that $(ZS) > (ZB)$, as required by the conditions mentioned earlier under BUFFER MEDIUM. (RCB) is thus a lower bound on (RC). Also, $(RC) \leq (RCC)$, where,

$$(RCC) = [\,(ZS)-(ZC)\,] \,/\, [\,(ZS)+(ZC)\,]$$

(ZC) is the couplant acoustic impedance. The quantity (RCC) is thus an upper bound on (RC).

We define $(RC) = (RCV)$ where (RCV) is the "valid" reflection coefficient. Then, $(RCB) \leq (RCV) \leq (RCC)$. (RCV) is determined by iterative regression analysis of the zoned raw data for B2/B1 vs. frequency.

The iterative regression routine assigns a starting value to (RCV) equal to (RCC). A two parameter multiple regression routine finds a succession of interim values for (C) and (M). A standard deviation is computed by comparing array values of the zoned raw data with interim ARC's computed from the current values of (M), (C), and (RCV). The regression proceeds for a series of decremented (RCV) values. For each iteration, a test is performed on the current standard deviation. This iterative process ends when: (a) the current standard deviation value is a minimum, or (b) $(RCV) \leq (RCB)$. The process repeats until the value for (RCV) is determined to a precision of at least four significant figures. An example of the iterative curve fitting is shown in fig. 9.

Two tests are made to determine the acceptability of the data at this stage: First, if $(RCV) < (RCB)$, all waveforms and associated data are rejected. Second, rejection also occurs if the coefficient of determination or goodness of fit (FIT) is less than a specified value (e.g., <0.998). In either case new waveforms must be acquired and the processing reinitiated.

5. REPRESENTATIVE RESULTS

5.1 ATTENUATION VS. FREQUENCY CURVE, AFC

Upon completion of the the ARC fitting process, the program returns values for (RCV), (M), and (C). These quantities are displayed and documented as shown by the examples in fig. 10. The solid line superimposed on the raw data in fig. 10 is the ARC or (BB) versus (F) found from,

$$LOGN(BB) = LOGN(RCV) - 2(ST)(C)(F)^{(M)}$$

Figure 10 shows results obtained with both versions of the waveform: the natural and the truncated. Differences that are evident in the corresponding raw ratios B2/B1 are explained under DISCUSSION.

Establishment of the ARC yields the parameters needed to define the functional relation sought between the attenuation coefficient and frequency. Some typical plots for the attenuation vs. frequency curve, AFC, appear in fig. 11. The solid curve superimposed on the raw data is based on the values for (M), (C), and the equation,

$$(ALPHA) = (C)(F)^{(M)}$$

The AFC characterizes the material sample microstructure and, therefore, certain material properties. Further analysis is needed to use information contained in the AFC.

5.2 MATERIAL CORRELATIONS

Correlations will exist with properties that are governed by the same microstructural factors that govern the velocity and attenuation parameters. For example, it has been found that certain material properties correlate closely with velocity and attenuation factors that can be derived from the AFC parameters. The significance of the previous signal processing results is explained in terms of correlations with fracture toughness and yield strength. The approach is to check the results against independently measured material properties obtained previously for a set of standard specimens. The standard specimens in the present case consist of 250-grade maraging steel. Prior mechanical tests established fracture toughness and yield strength for these specimens.

5.3 VELOCITY AND SLOPE FACTORS

There are several ultrasonic attenuation factors that correlate with material properties. These factors derive from the AFC parameters (C) and (M), as explained next.

Since attenuation is a strong function of frequency, it is necessary to specify particular frequencies that are relevant for material property correlations. There are two factors based on the first derivative or slope of the AFC at specific frequencies: One factor is the slope (BETA1) which is d(ALPHA)/d(F) evaluated at the frequency corresponding to an attenuation coefficient of unity or, (ALPHA)=1. The other factor is the slope (BETA2) which is d(ALPHA)/d(F) evaluated at a frequency corresponding to a particular wavelength. This is the wavelength marking the transition from Rayleigh to stochastic scattering. It is defined in terms of the mean grain size (GS) of the material. Expressions for these factors are(2),

$$\mathrm{LOGN(BETA1)} = \mathrm{LOGN(M)} + [\mathrm{LOGN(C)}]/(\mathrm{M})$$

$$\mathrm{LOGN(BETA2)} = \mathrm{LOGN}[(\mathrm{M})(\mathrm{C})] + [(\mathrm{M})-1]\{\mathrm{LOGN}[(\mathrm{VL})/(\mathrm{GS})]\}$$

According to refs. 2,5 the quantity (BETA1) increases linearly with plane strain fracture toughness (KIC) for material samples of a maraging steel if all samples have the same yield strength (YS). The product of velocity with (BETA2)/(M), that is, (VL)(BETA2)/(M), varies exponentially with the quantity $(KIC)^2/(YS)^2$ for the maraging steel. These relations are shown in figs. 12(a) and 12(b). In fig. 12 data obtained by digital waveform processing are compared with previous data obtained by analog methods described in ref. 2.

5.4 DISCUSSION

Ultimately, the usefulness of any set of velocity or attenuation measurements or derived quantities must be judged on the basis of capability for characterizing material properties with good accuracy. The digital waveform processing methods described herein appear viable from this standpoint. For example, the data in figs. 12(a) and 12(b) confirm the strong correlations that were expected between the ultrasonic factors and fracture toughness and yield strength.

In figs. 12(a) and 12(b) the slight difference between the regression lines for digital and analog data is due primarily to differences in the reflection coefficients used. In the manual analog method the reflection coefficient was taken as (RCC), because it was inferred to be appropriate based on the available data. The automatic digital method, on the other hand, produces considerably more data and better resolution in the frequency domain. It becomes clear that (RCC) is only an upper bound on the reflection coefficient.

It is noteworthy that the ARC intercepts the ordinate asymptotically to (RCV) between (RCC) and (RCB), as in figs. 8 and 10. (RCV) which is based on the ARC is thus the "valid" reflection coefficient relative to the high frequency data in the valid zone. Moreover, when good coupling is attained by applying adequate force, (RCV) tends closer to (RCB). This is expected if the buffer is tightly coupled to the material sample surface.

Waveform truncation results revealed an interesting aspect of the trailing oscillations in the natural waveform. The truncation criterion was to retain only the five symmetrical leading oscillations, and to discard the small trailing oscillations. Once a waveform meets the acceptance criteria, given previously, it is a simple matter to perform the truncation precisely and reproducibly using digital waveform processing. The discarded trailing oscillations of the natural waveform are assumed to be due chiefly to multiple residual reflections in the couplant. This is confirmed by comparing the ARC raw data for natural and trucated waveforms as follows:

The raw data in figs. 10(a) and 10(b) reveal the effects of truncation in the diffraction regime, to the left of the valid zone. It is apparent in fig. 10(b) that truncation eliminates the effects of couplant multiple reflection seen in fig. 10(a).

These multiple reflection effects are apparently due to couplant thickness variations since the surfaces are neither prefectly mated nor ideally planar. Hence, in the low frequency regime, the longer wavelengths are likely to interact with a greater portion of the coupled area. The result is the anomalous behavior of the raw data in the diffraction regime. In the diffraction regime the reflection coefficient (RC) is a variable that depends on the coupling medium, wavelength, and ultrasonic beam cross section[7]. The anomolous reflection effects can be avoided as demonstrated by the ARC which is based only on data in the high frequency regime (valid zone). The reflection coefficient (RCV) is thus established independently of the anomalous effects in the diffraction regime.

Clearly, automated digital waveform processing methods will provide the experimentalist additional information that is either unavailable or impractical to obtain with manual analog methods. This additional information is gained through the computer's ability to process massive amounts of data. This affords access to data that is readily available only by means of complex analytical treatments such as the fast Fourier transform and array processing routines.

6. SUMMARY AND CONCLUSIONS

A computerized waveform processing system and its operational details are described. The system was dedicated to ultrasonic velocity and attenuation measurements relative to evaluation of material properties. The system serves simultaneously as a tool for ultrasonic research and for establishing material property correlations.

The system and methods described herein are essentially prototypical. They demonstrate some practical approaches to ultrasonic nondestructive materials evaluation. More work is needed to improve the operating processes and instrumentation. Among the advancements needed are:

(1) Faster algorithms in machine language for some aspects of data processing not currently covered by existing software

(2) Fully programmable instruments and modules for ultrasonic signal generation, acquisition, and amplification

(3) More powerful and more sensitive transducers and instruments for use over greater frequency ranges (to several hundred megahertz)

It is apparent that high speed digital waveform processing over a wider frequency range will enable more detailed ultrasonic measurements for material property evaluations. Similar measurement have been previously accomplished by manual analog methods that are tedious and time consuming while giving less detailed data. Without computer automation the necessary measurements for material property evaluations would certainly be impractical either in production or laboratory situations requiring speed, economy, and accuracy.

The experience gained thus far indicates that further development of computer waveform processing in high frequency ultrasonics will contribute to:

(1) Establishing a powerful research tool for ultrasonic investigations.

(2) Practical applications for material property verification and control.

(3) Investigation of factors governing material strength.

7. ACKNOWLEDGEMENT

The author gratefully acknowledges the skillful programming performed by David R. Hull, the results of which constitute many of the data and figures presented in this report.

8. REFERENCES

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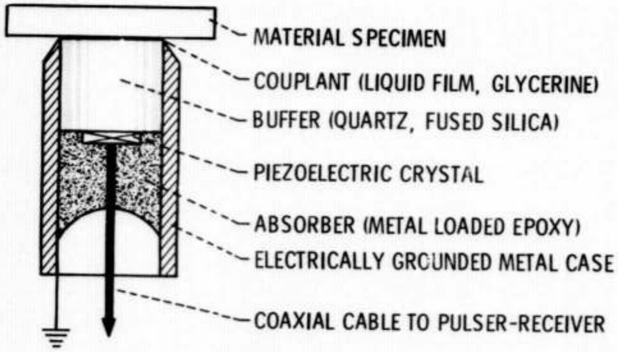


Figure 1. - Cross section of buffered broadband ultrasonic probe for velocity and attenuation measurements with the multiple pulse echo method.

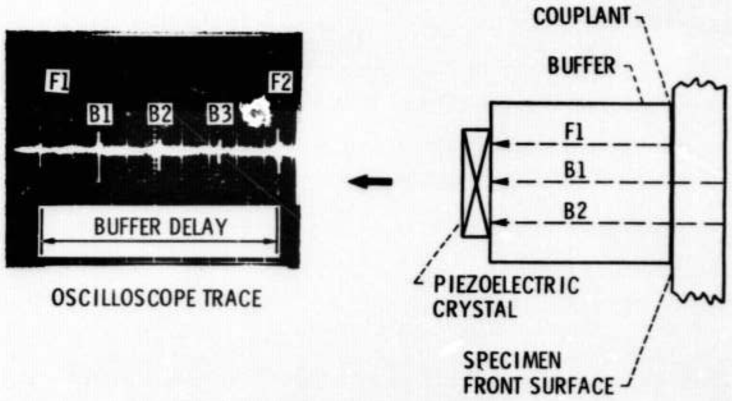


Figure 2. - Typical time domain trace of multiple echoes within buffer delay in pulse-echo probe. F1 is first echo from specimen front surface, B1 and B2 are first and second echoes, respectively, from specimen back (free) surface.

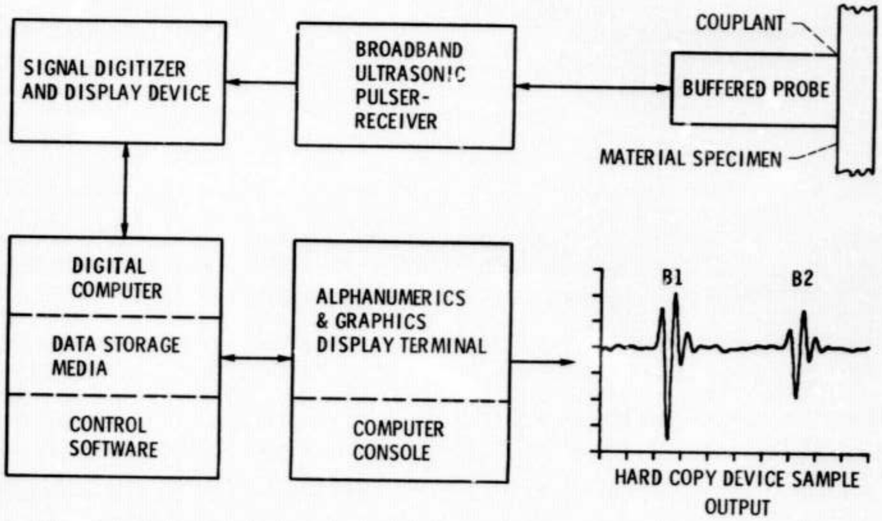
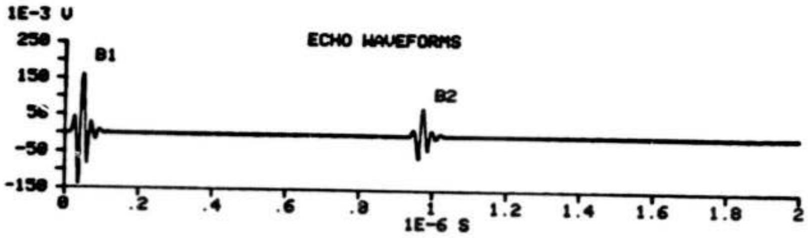
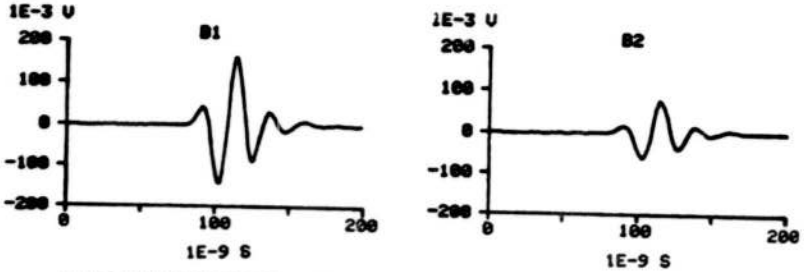


Figure 3. - Block diagram of computer system for ultrasonic signal acquisition and processing for pulse-echo velocity and attenuation measurement.



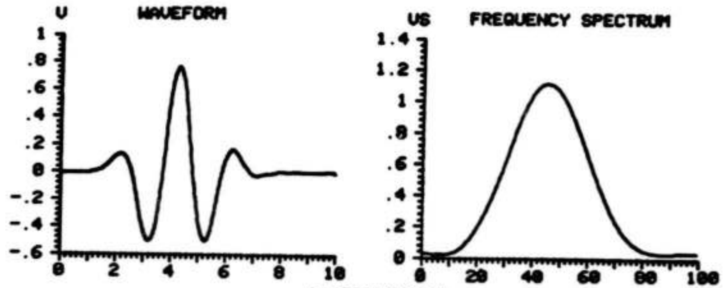
(a) COMPOSITE WAVEFORM SYNTHESIZED FROM TWO 512 ELEMENT ARRAYS.



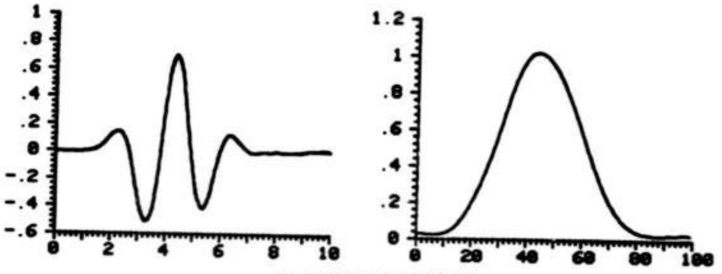
(b) 512 ELEMENT WAVEFORM ARRAY FOR B1.

(c) 512 ELEMENT WAVEFORM ARRAY FOR B2.

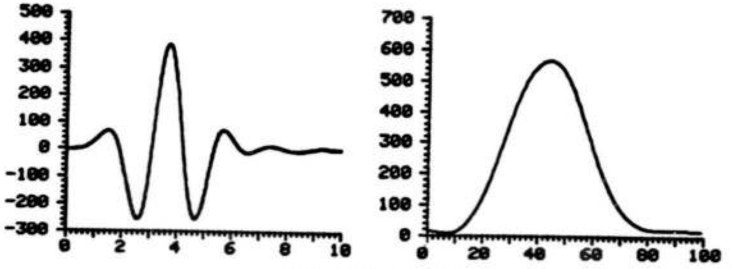
Figure 4. - Echo waveforms for B1 and B2 indicating signal resolution improvement obtained by digitizing each echo into a separate 512 element array. In (b) and (c) echoes B1 and B2, respectively, are digitized in a 200 nanosecond window. The composite waveform (a) shows the long delay, approximately 900 nanoseconds, between B1 and B2 typical for the material specimens used in this study.



(a) IDEAL SIGNAL

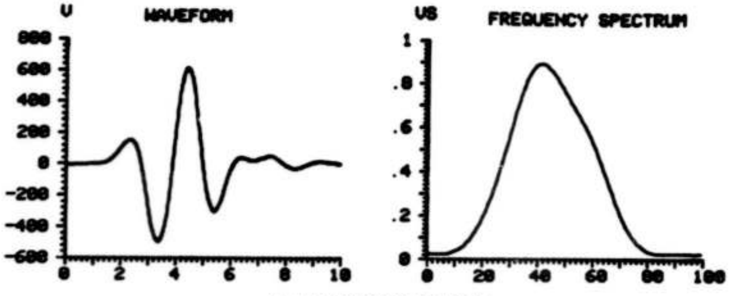


(b) ACCEPTABLE SIGNAL

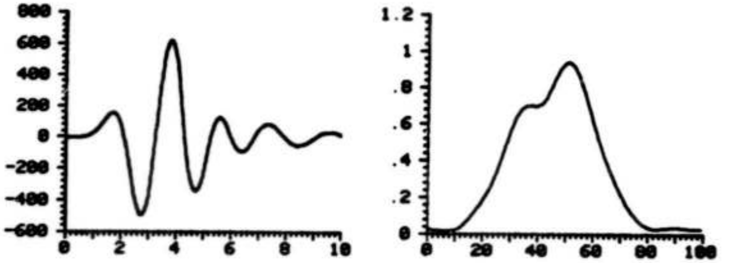


(c) ACCEPTABLE SIGNAL

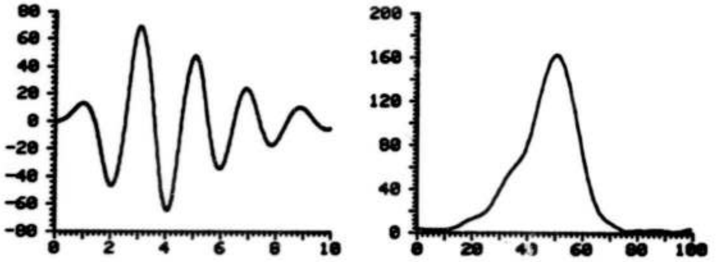
Figure 5. - Waveforms and frequency spectra associated with acceptable and unacceptable signals. Unacceptable signals arise chiefly from poor coupling, improper damping, or impedance mismatch. The waveform vertical scale is in arbitrary volts and the horizontal scale is in nanoseconds. The frequency spectrum vertical scale is in arbitrary volt-seconds and the horizontal scale is in megahertz.



(d) UNACCEPTABLE SIGNAL.



(e) UNACCEPTABLE SIGNAL.



(f) UNACCEPTABLE SIGNAL.

Figure 5. - Concluded.

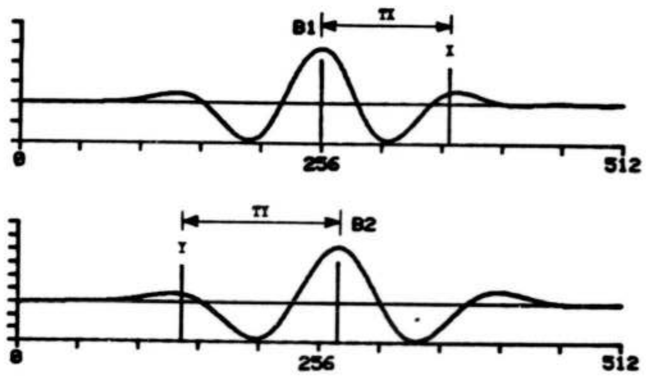
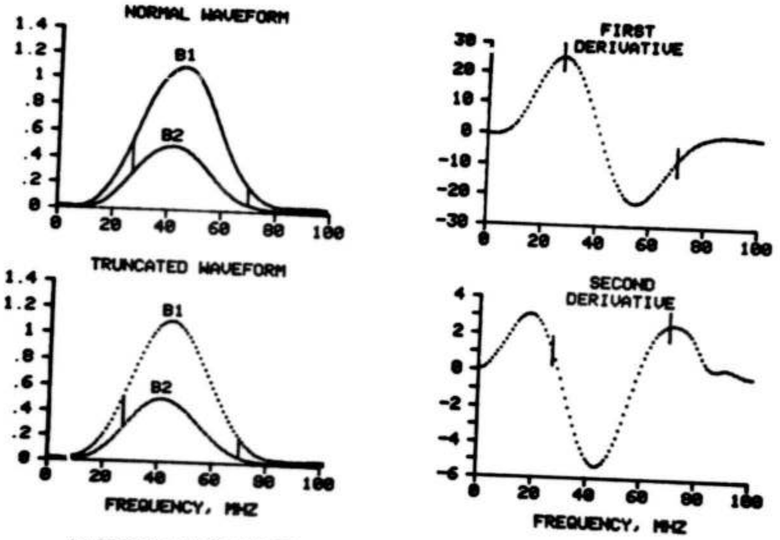


Figure 6. - Illustration of basis for velocity computation using pulse train. Vertical markers X and Y indicate the peaks of pulses associated with echoes B1 and B2, respectively. In the illustration the centroid of B1 leads by (TX) and the centroid of B2 lags by (TY). Pulse X leads pulse Y by the pulse period (TP). The waveforms are shown as 512 element arrays. Vertical and horizontal scale factors are arbitrary.



(a) SPECTRA OF B1 AND B2.

(b) DERIVATIVES OF B2.

Figure 7. - Frequency spectra and the first and second derivatives of the spectra for typical signals after digitization and computer processing. The truncated version of the spectrum of B2 in (a) is used to obtain the first and second derivatives in (b). The derivatives are used as indicated by the vertical markers to define the "valid zone" or useable frequency range.

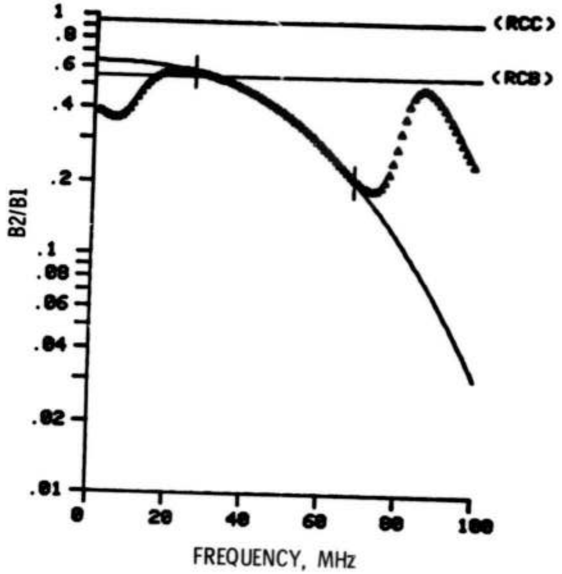


Figure 8. - Typical amplitude ratio curve, ARC, showing a plot of raw data (triangles) for the ratio B2/B1 over the frequency range from 0 to 100 megahertz. The solid curve is fitted to data in the valid zone indicated by the vertical markers. (RCC) is the reflection coefficient computed for the couplant and (RCB) is the reflection coefficient computed for the buffer.

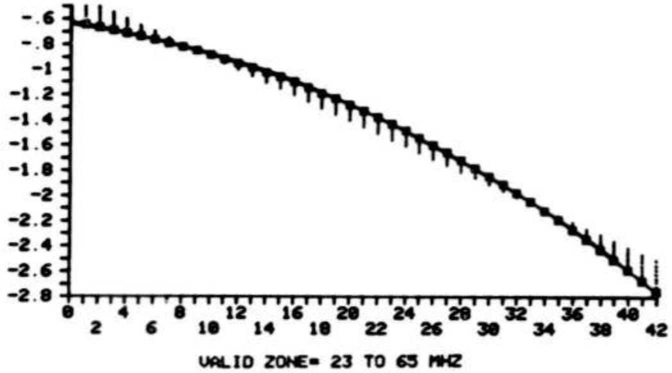
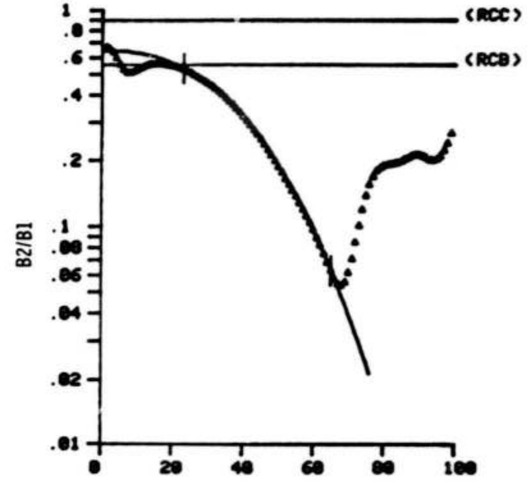
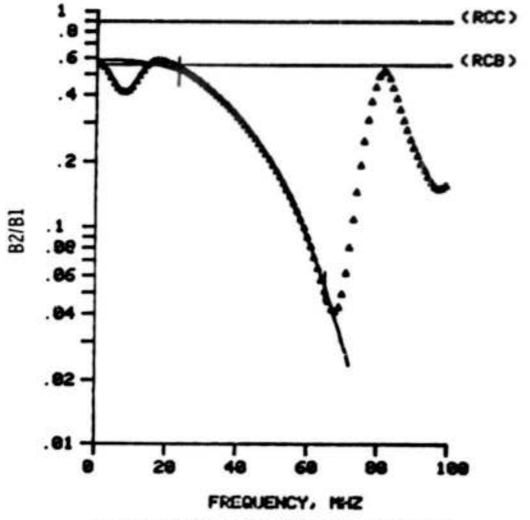


Figure 9. - Amplitude ratio curve fitting process. In this example the valid zone is from 23 to 65 megahertz, a frequency range of 42 megahertz as indicated by the abscissa. The ordinate scale is proportional to the logarithm of the amplitude ratio B2/B1. The vertical columns of dots represent trial curves in the iterative regression process. The solid line through the squares is the final fitted curve.

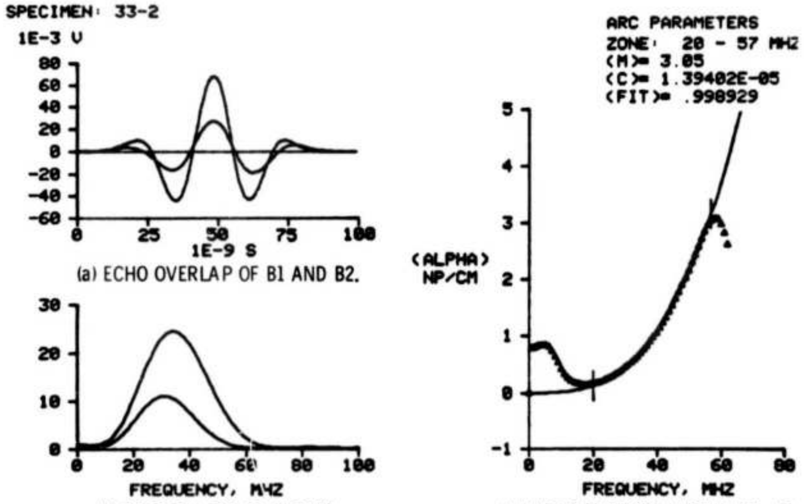


(a) ARC BASED ON NATURAL WAVEFORM SPECTRA.



(b) ARC BASED ON TRUNCATED WAVEFORM SPECTRA.

Figure 10. - Amplitude ratio curves, ARC's for natural and truncated waveforms illustrating the anamolous effect in the diffraction regime, to the left of the upper valid zone marker.

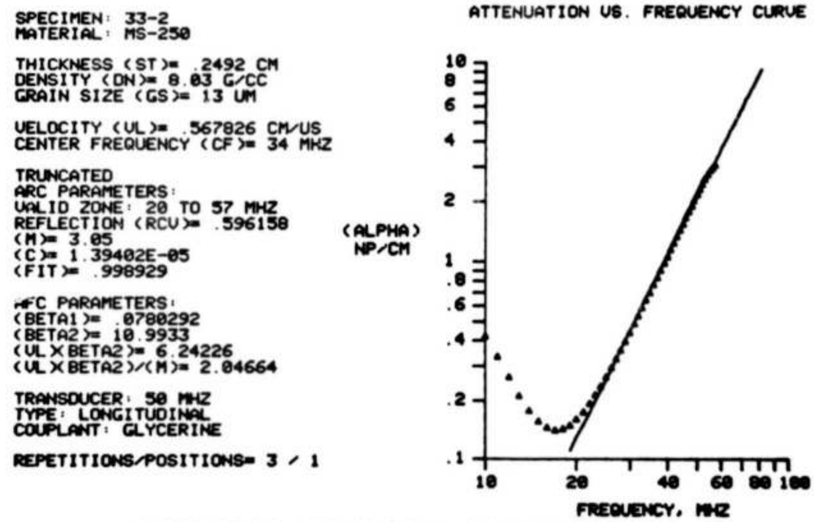


(a) ECHO OVERLAP OF B1 AND B2.

(b) SPECTRA FOR B1 AND B2.

(c) LINEAR PLOT OF (ALPHA) VS. (F).

Figure 11. - Computer documentation of data for maraging steel specimen 33-2. Result of echo overlap routine used for computing velocity is shown in (a). Valid zone for determining ARC parameters is indicated by vertical markers in (c). Final documentation of input data, conditions, and processing results is illustrated in (d).



```
SPECIMEN: 33-2
MATERIAL: MS-250

THICKNESS (ST)= .2492 CM
DENSITY (DN)= 8.03 G/CC
GRAIN SIZE (GS)= 13 UM

VELOCITY (VL)= .567826 CM/US
CENTER FREQUENCY (CF)= 34 MHZ

TRUNCATED
ARC PARAMETERS:
VALID ZONE: 20 TO 57 MHZ
REFLECTION (RCV)= .596158
(M)= 3.05
(C)= 1.39402E-05
(FIT)= .998929

AFC PARAMETERS:
(BETA1)= .0780292
(BETA2)= 10.9933
(VL X BETA2)= 6.24226
(VL X BETA2)/(M)= 2.04664

TRANSDUCER: 50 MHZ
TYPE: LONGITUDINAL
COUPLANT: GLYCERINE

REPETITIONS/POSITIONS= 3 / 1
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(d) SPECIMEN DATA AND LOGARITHMIC PLOT OF (ALPHA) VS. (F).

Figure 11. - Concluded.

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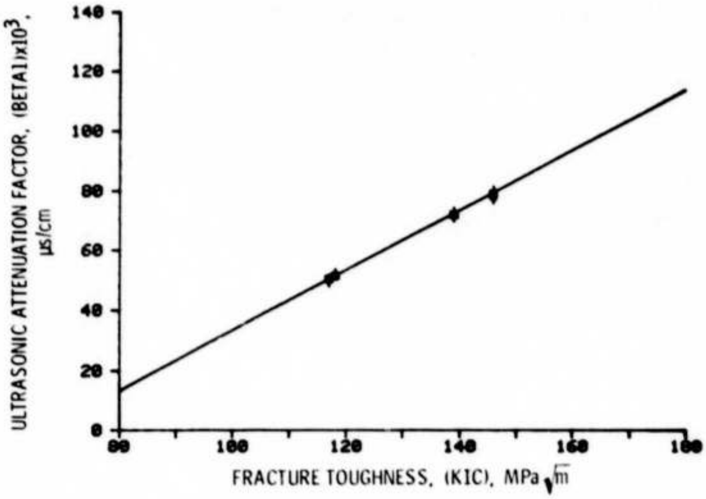
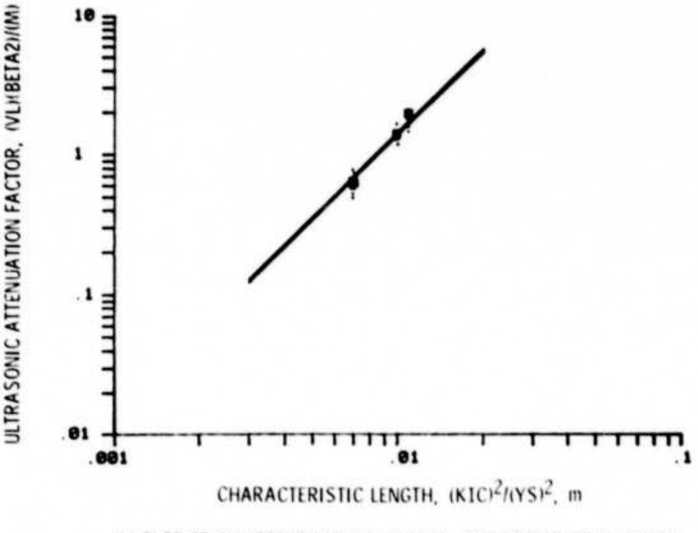


(a) PLOT OF (BETA1) VALUES VS. FRACTURE TOUGHNESS.



(b) PLOT OF (VL)(BETA2)/(M) VALUES VS. CHARACTERISTIC LENGTH.

Figure 12. - Comparison of ultrasonic attenuation factors with theoretical curves (solid lines) for four maraging steel (250-grade) specimens.