Standard Test Method for Measuring Ultrasonic Velocity in Advanced Ceramics with Broadband Pulse-Echo Cross-Correlation Method[1]

This standard is issued under the fixed designation C1331; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes a procedure for measurement of ultrasonic velocity in structural engineering solids such as monolithic ceramics, toughened ceramics, and ceramic matrix composites.

1.2 This test method is based on the broadband pulse-echo contact ultrasonic method. The procedure involves a computer-implemented, frequency-domain method for precise measurement of time delays between pairs of echoes returned by the back surface of a test sample or part.

1.3 This test method describes a procedure for using a digital cross-correlation algorithm for velocity measurement. The cross-correlation function yields a time delay between any two echo waveforms (**1**).[2]

2. Referenced Documents

2.1 *ASTM Standards:*[3]

B311 Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity

C373 Test Method for Water Absorption, Bulk Density, Apparent Porosity, and Apparent Specific Gravity of Fired Whiteware Products, Ceramic Tiles, and Glass Tiles

E494 Practice for Measuring Ultrasonic Velocity in Materials

E1316 Terminology for Nondestructive Examinations

2.2 *ASNT Document:*

Recommended Practice SNT-TC-1A for Nondestructive Testing Personnel Qualification and Certification[4]

2.3 *Military Standard:*

MIL-STD-410 Nondestructive Testing Personnel Qualification and Certification[5]

2.4 *Additional references are cited in the text and at end of this document.*

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *back surface*—the surface of a test sample which is opposite to the front surface and from which back surface echoes are returned at normal incidence directly to the transducer.

3.1.2 *bandwidth*—the frequency range of an ultrasonic probe, defined by convention as the difference between the lower and upper frequencies at which the signal amplitude is 6 dB down from the frequency at which maximum signal amplitude occurs.

3.1.3 *broadband transducer*—an ultrasonic transducer capable of sending and receiving undistorted signals over a broad bandwidth, consisting of a thin damped piezocrystal in a buffered probe (search unit).

3.1.4 *buffered probe*—an ultrasonic search unit as defined in Terminology E1316 but containing a delay line, or buffer rod, to which the piezocrystal is affixed within the search unit housing and which separates the piezocrystal from the test sample (Fig. 1).

3.1.5 *buffer rod*—an integral part of a buffered probe, usually a quartz or fused silica cylinder that provides a time delay between the excitation pulse from the piezocrystal and echoes returning from a sample coupled to the free end of the buffer rod.

3.1.6 *cross-correlation function*—the cross-correlation function, implemented by a digital algorithm, yields a time delay between any two (ultrasonic) echo waveforms. This time is used to determine velocity (**1**).

[1] This test method is under the jurisdiction of ASTM Committee C28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.03 on Physical Properties and Non-Destructive Evaluation.

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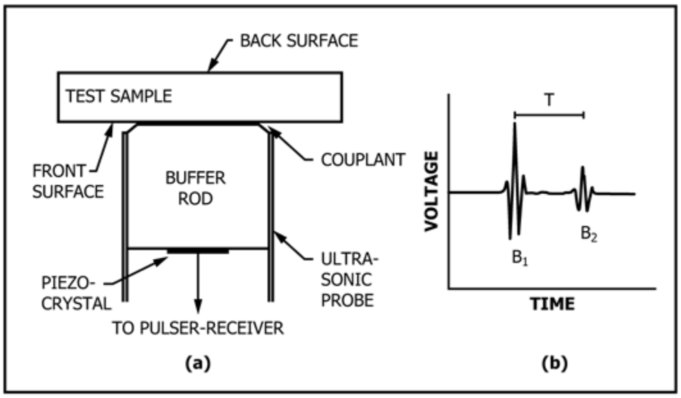
[2] The boldface numbers in parentheses refer to the list of references at the end of this test method.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

[5] Available from Standardization Documents Order Desk, DODSSP, Bldg. 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5098, http://www.dodssp.daps.mil.



NOTE 1—B_1 and B_2 are first and second back surface echoes, respectively, and T is time interval between the echoes.

FIG. 1 Cross Section of Buffered Ultrasonic Probe (a) and Principle Echoes (b) for Velocity Measurement

3.1.7 *dispersion*—variation of ultrasonic velocity as a function of wavelength, that is, frequency dependence of velocity.

3.1.8 *front surface*—the surface of a test sample to which the buffer rod is coupled at normal incidence (designated as test surface in Terminology E1316.

3.1.9 *group velocity*—velocity of a broadband ultrasonic pulse consisting of many different component wavelengths.

3.1.10 *test sample*—a solid coupon or material part that meets the constraints needed to make the ultrasonic velocity measurements described herein, that is, a test sample or part having flat, parallel, smooth, preferably ground or polished opposing (front and back) surfaces, and having no discrete flaws or anomalies unrepresentative of the inherent properties of the material.

3.1.11 *wavelength (λ)*—distance that sound (of a particular frequency) travels during one period (during one oscillation), λ = v/f, where v is the velocity of sound in the material and where velocity is measured in cm/µs, frequency in MHz, and wavelength in cm, herein.

3.2 Other terms or nomenclature used in this test method are defined in Terminology E1316.

4. Significance and Use

4.1 The velocity measurements described in this test method may be used to characterize material variations that affect mechanical or physical properties. This procedure is useful for measuring variations in microstructural features such as grain structure, pore fractions, and density variations in monolithic ceramics.

4.2 Velocity measurements described herein can assess subtle variations in porosity within a given material or component, as, for example, in ceramic superconductors and structural ceramic specimens (**2**,**3**).

4.3 In addition to ceramics and ceramic composites, the velocity measurements described herein may be applied to polycrystalline and single crystal metals, metal matrix composites, and polymer matrix composites.

4.4 An alternative technique for velocity measurement is given in Practice E494.

5. Personnel Qualifications

5.1 It is recommended that nondestructive evaluation/examination personnel applying this test method be qualified in accordance with a nationally-recognized personnel qualification practice or standard such as ASNT SNT-TC-1A, MIL STD 410, or a similar document. The qualification practice or standard used and its applicable revision(s) should be specified in a contractual agreement.

5.2 Knowledge of the principles of ultrasonic testing is required. Personnel applying this test method should be experienced practitioners of ultrasonic examinations and associated methods for signal acquisition, processing, and interpretation.

5.3 Personnel should have proficiency in computer signal processing and the use of digital methods for time and frequency domain signal analysis. Familiarity with Fourier and associated transforms for ultrasonic spectrum analysis is required.

6. Apparatus and Test Sample

6.1 Instrumentation (Fig. 1 and Fig. 2) for broadband cross-correlation pulse-echo ultrasonic velocity measurement should include the following:

6.1.1 *Buffered Probe:*

6.1.1.1 The buffer rod, which is an integral part of the probe (search unit), should be a right cylinder with smooth flat ends normal to the axis of the probe.

6.1.1.2 The center frequency of the buffered probe should produce a wavelength within the sample that is less than one fifth of the thickness of the sample.

6.1.1.3 The buffer rod length, that is, time delay should be three times the interval between two successive back surface echoes.

6.1.1.4 The wave mode may be either longitudinal or shear.

6.1.2 *Pulser-Receiver,* with a bandwidth that is at least twice that of the buffered probe. The bandwidth should include frequencies in the range from 100 kHz to over 100 MHz.

6.1.2.1 The pulser-receiver should have provisions for controlling the pulse repetition rate, pulse energy level, pulse damping, and received signal gain.

6.1.2.2 The pulser-receiver should provide a synchronization pulse and signal output connector.

6.1.3 *Waveform Digitizing Oscilloscope (A/D Board),* bus programmable, to window and digitize the echo waveforms.

6.1.3.1 A minimum 512-element waveform array with a maximum data sampling interval of 1.95 ns is recommended. For better waveform resolution, a 1024-element array with a data sampling interval of 0.97 ns may be needed.

6.1.3.2 *Vertical Amplifier,* bus programmable module.

6.1.3.3 *Time Base,* bus programmable module with a resolution of at least 5 ns per division and several time base ranges including a fundamental time base of at least 200 ns.

6.1.4 *Digital Time Delay Module,* bus programmable, to introduce a known time delay between the start of two separate time gates, that is, windows each of which containing one of two successive back surface echoes.

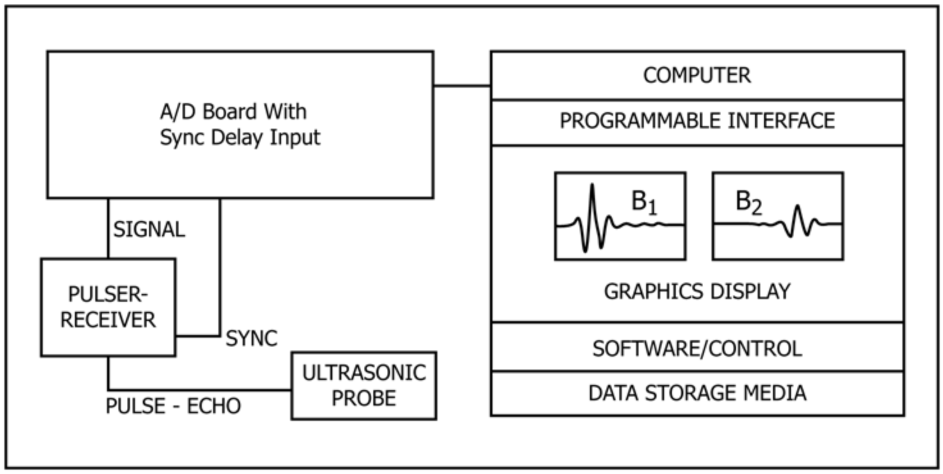


FIG. 2 Instrumentation Diagram for Acquiring and Separately Windowing Two Successive Back Surface Echoes, B_1 and B_2, for Cross-Correlation Velocity Measurement

6.1.4.1 Separate windows are preferred for waveform digitization. Each waveform should occupy from 60 to 80 % of the window.

6.1.4.2 The time synthesizer should have an accuracy of ±1 ns with a precision of ±0.1 ns.

6.1.5 *Video Monitors,* (optional) one analog, one digital for real-time visual inspection of echo waveforms and for making interactive manual adjustments to the data acquisition controls.

6.1.6 *Computer,* with adequate speed and storage capacity to provide needed software control, data storage, and graphics capability. The software should include a fast Fourier transform (FFT) algorithm package containing the cross-correlation algorithm.

6.1.7 *Couplant Layer,* to establish good signal transfer between the buffer rod and test sample. The layer should be as thin as possible to minimize couplant resonances and distortion of the echo waveforms.

6.1.7.1 The couplant should not be absorbed by or be otherwise deleterious to the test sample.

6.1.7.2 Dry coupling with a thin polymer may be used where liquid contamination by or absorption of liquids by the test sample or part must be avoided.

6.2 The test sample or part should have flat parallel opposing surfaces in the region where the velocity measurements are made. This will assure good coupling between the transducer and sample and also produce valid echoes for velocity measurements.

6.2.1 Lack of precision in the measurement of the test sample thickness can undermine the nanosecond precision with which pulse-echo travel times can be measured. Therefore, the sample thickness should be measurable to an accuracy of ±0.1 % or better.

6.2.2 For most engineering solids, the sample thickness should be at least 2.5 mm. There is a practical upper bound on sample thickness, for example, if the sample is too thick, there may be considerable signal attenuation, beam spreading, and dispersion that render the signal useless.

7. Procedure

7.1 Use instrument control software routines to start and control the interface bus; perform procedures such as optimizing intensity, voltage, and time on the waveform digitizing oscilloscope; control the digital time delay module; and acquire, store, and process data.

7.1.1 A cross-correlation algorithm should be part of the FFT software.

7.1.2 The arguments needed to implement the cross-correlation algorithm are the time domain waveform arrays, that is, digitized echoes B_1 and B_2 (Fig. 1).

7.2 Prepare samples with front and back surfaces that are sufficiently smooth, flat, and parallel to allow measurement of the test sample thickness to an accuracy of 0.1 % or better.

7.3 Couple the sample to the transducer to obtain two strong back surface echoes.

7.3.1 Apply pressure to minimize the couplant layer thickness. A backing fixture may be necessary to apply pressure.

7.3.2 Care shall be taken to avoid coupling the sample to the backing fixture and thereby losing echo signal strength by leakage.

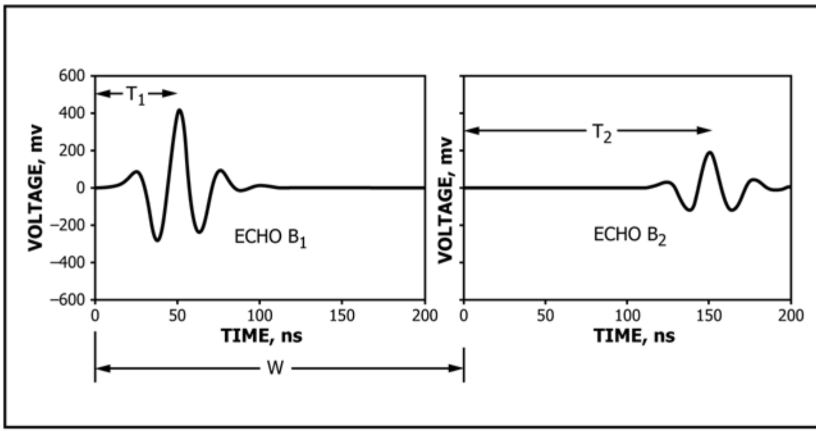
7.3.3 A dry, hard rubber or composite material with a rough-machined or sawtooth surface is recommended for the backing fixture.

7.4 Determine the precise positions, in the time domain, of the start of the windows containing echo waveforms B_1 and B_2 and program the digital time delay module to sequentially set these delays.

7.4.1 The oscilloscope time base should be adjusted so that each waveform occupies 60 to 80 % of its window. Window fill may be as low as 20 % and still produce acceptable results.

7.4.2 During data acquisition, the time synthesizer should sequence through the predetermined time positions.

7.5 The waveform digitizing oscilloscope (A/D device) should be programmed to automatically maximize the echo waveform amplitude and intensity settings.



NOTE 1—Time delay, W, between the two window start times is predetermined. Time interval, T, between echoes B_1 and B_2 is calculated from $T = W + (T_2 - T_1)$.

FIG. 3 Separately Windowed and Digitized Back Surface Echoes B_1 and B_2

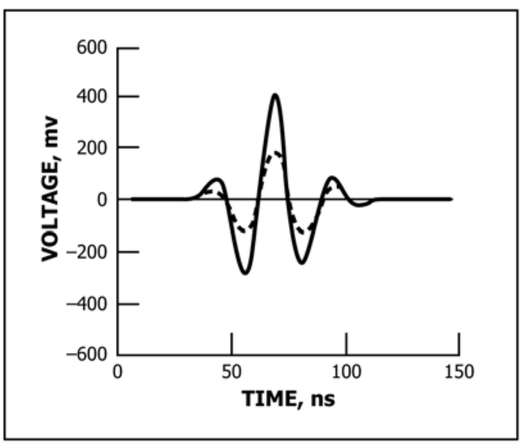


FIG. 4 Results of Digital Overlap of Echoes B_1 (Solid Line) and B_2 (Dotted Line) When Dispersion is Not Present

7.6 Digitize back surface echoes B_1 and B_2 into separate 512-element waveform arrays. Signal averaging may be necessary to accurately capture subtle features of the waveforms. Signals with high SNR (signal-to-noise ratio) can be accurately digitized by only a few signal averagings while signals with low SNR may require as much as 32 signal averagings.

7.7 Ultrasonic velocity is determined by measuring the time delay between two successive echoes returned by the back surface of the test sample. These are shown as the two separately-windowed echoes B_1 and B_2 (Fig. 3).

7.7.1 Echoes B_1 and B_2 are separately windowed to get maximum time and voltage resolution. This is done by presetting the digital time delay module to produce two windows that capture echoes B_1 and B_2 with window start times D_1 and D_2, respectively.

7.7.1.1 The centroid of echo B_1 occurs at time $D_1 + T_1$.

7.7.1.2 The centroid of echo B_2 occurs at time $D_2 + T_2$.

7.7.2 If the sample thickness and other constraints are met, it should be possible to digitally overlap echoes B_1 and B_2 as in Fig. 4. Dispersion has occurred if echo B_2 is spread out relative to B_1 and does not have the same zero crossings as B_1 . If too pronounced, dispersion and beam spreading may be avoided by reducing the sample thickness.

7.7.3 The travel time interval T between B_1 and B_2 is given by $T = C + W$, where $W = D_2 - D_1$ and C is the echo displacement time obtained by means of the cross-correlation algorithm.

7.7.4 The cross-correlation algorithm is applied to the echo waveforms B_1 and B_2 to provide the value for the echo displacement time C.

7.8 After acquiring waveform records for echoes B_1 and B_2, use the cross-correlation algorithm to obtain the echo displacement time, C, relative to the zero reference.

7.9 Use the cross-correlation algorithm which transforms B_1 and B_2 into the frequency domain, multiplies the complex conjugate of $B_2(f)$ by $B_1(f)$, and transforms the result back to the time domain as a cross-correlation function.

7.9.1 The echo displacement time C equals the time displacement of the cross-correlation function maximum from the zero of the cross-correlation function (Fig. 5).

7.9.1.1 If $T_1 = T_2$, then $C = 0$ as in Fig. 5a.

7.9.1.2 If $T_1 < T_2$, then $C > 0$ as in Fig. 5b.

7.9.1.3 If $T_1 > T_2$, then $C < 0$ as in Fig. 5c.

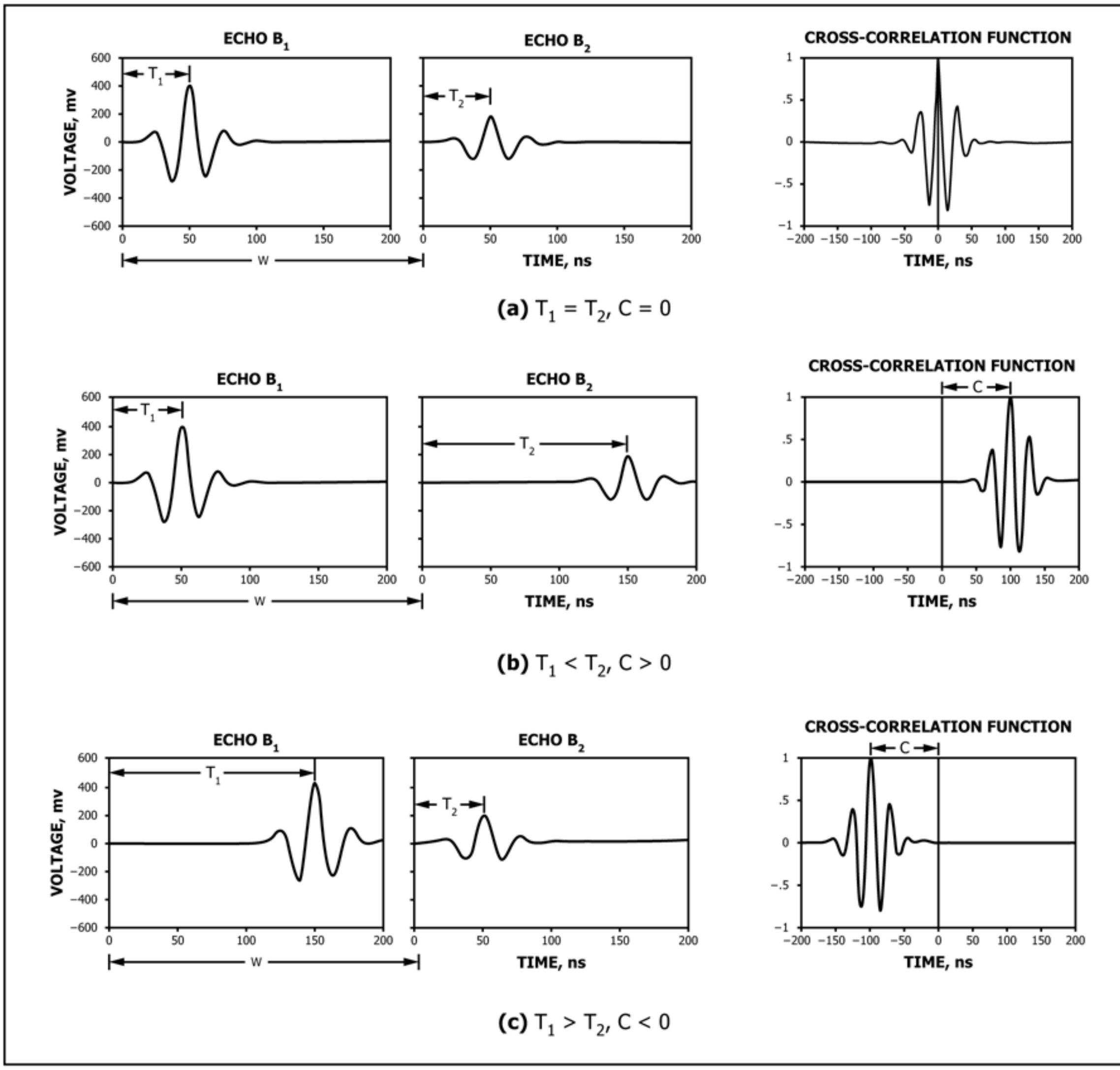
7.9.2 In some cases, because of the nature of the test sample material, echo B_2 may be inverted relative to B_1. In these cases the *echo displacement time* equals the displacement of the cross-correlation function *minimum* from the zero of the cross-correlation function.

7.9.2.1 Confusion may be avoided by programming the system to determine the *echo displacement time* from the absolute maximum of the cross-correlation function.

7.10 Calculate the time delay between B_1 and B_2, that is $T = W + C$.

7.11 Calculate velocity from $v = 2s/T$, where s is the sample thickness and T is time delay as determined in 7.10.

7.12 Velocity determined by means of the cross-correlation function is a group velocity within the frequency bandwidth of the buffered probe and is statistically weighted by the probe center frequency.



NOTE 1—That is, (a) when $T_1 = T_2$, (b) when $T_1 < T_2$, and (c) when $T_1 > T_2$.

FIG. 5 Representation of Three Possible Cases Relating to Echo Displacement Time *C* to Position of Echo Waveforms B_1 and B_2 in Their Respective Windows

7.13 An alternative procedure may be used wherein echo waveforms B_1 and B_2 are digitized simultaneously, that is, both may appear in the same window (Fig. 6), provided that they are not separated by a large time interval and can be digitized with sufficient resolution (data sampling interval of 1.95 ns per waveform).

7.13.1 In this case $W = 0$ and $T = C$, but the cross-correlation function shall still be determined by transforming B_1 and B_2 separately. This is done by assigning zero values to that part of the dual waveform array corresponding to B_1 while leaving B_2 intact and then zeroing B_2 while leaving B_1 intact.

7.13.2 As indicated in Fig. 6, this procedure was successively applied to back surface echo pairs B_1 and B_2 and then to the much weaker, noisier subsequent echo pair B_3 and B_4.

8. Report

8.1 Report the following information regarding the test sample or part examined:

8.1.1 ASTM or other standard designation of the material (for example, Alpha Silicon Carbide).

8.1.2 If appropriate, heat treatment or other conditioning of the material (for example, sintering of ceramics).

8.1.3 If appropriate, microstructure (for example, mean grain size, second phase content, percent porosity, mean pore size) including representative photomicrographs and documentation of the method used.

8.1.4 Sample thickness, lateral size, surface finish, and density.

8.2 Report the following information regarding the apparatus:

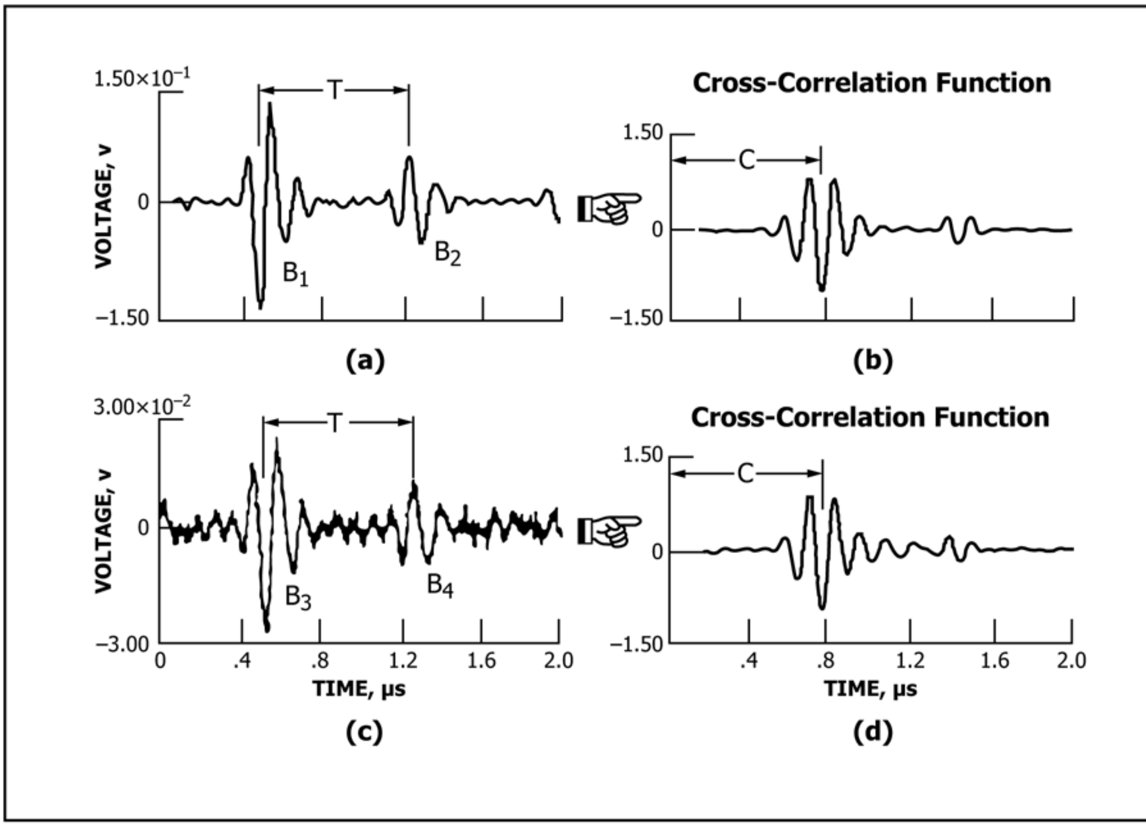
8.2.1 *Description of the Buffered Probe:*

8.2.1.1 Center frequency and bandwidth.

8.2.1.2 Buffer rod material, length and diameter.

8.2.1.3 Wave mode: longitudinal or shear wave.

8.2.2 Description/nature of the couplant fluid/material.



NOTE 1—The cross-correlation function (b) and (c) gives virtually identical time interval, $T = C$, when applied to either echo pair $B_1 - B_2$ (a) or $B_3 - B_4$ (c). Note that this example shows echo inversion and that the *echo displacement time C* is measured from the *minimum* of the cross-correlation function.

FIG. 6 Cross-Correlation Velocity Measurement Applied to Increasingly Weak and Noisy Signals in a Composite Sample

8.2.3 Description of the pulser-receiver: bandwidth and settings.

8.2.4 Diagram of mechanical apparatus and computer system.

8.3 Report the following information regarding velocity measurements:

8.3.1 Measured group velocity, in cm/µs, at the center frequency, in MHz, of the transducer.

8.3.2 If several transducers with different center frequencies are used, tabulate the group velocities measured by each along with their center frequencies.

8.3.3 Show typical/specimen ultrasonic waveforms (optional).

9. Precision and Bias

9.1 Because of the nature of the materials and lack of a wide database on advanced ceramics, no definitive statement can be made at this time concerning the precision and bias of this test method. However, the following should be observed in order to optimize precision and accuracy.

9.2 Errors in velocity measurements (**4, 5**) arise from the following:

9.2.1 Inaccuracies in thickness measurement caused by limitations of the thickness measuring device and by rough, wavy, or nonparallel sample surfaces.

9.2.2 Dispersion of diffraction (beam spreading) if the sample too thick.

9.2.3 Sidewall effects in narrow test samples; thick couplant layers; and rough, wavy, or nonparallel front and back sample surfaces.

9.2.4 Poor time base precision or inaccurate delay settings or readings.

9.3 Thickness measurement errors may outweigh all other sources of error and should be minimized by using the thickest samples practicable.

9.4 Errors due to beam spreading or diffraction may be minimized by utilizing probes with high center frequencies (**6**).

10. Remarks

10.1 The cross-correlation algorithm used in this test method does not require threshold values or other explicit criteria for accepting or rejecting specific features in echoes. The cross-correlation algorithm is especially advantageous when ultrasonic signals are distorted or have low signal-to-noise ratios as in porous ceramics or composites as illustrated in Fig. 6.

10.2 The cross-correlation velocity measurement technique described herein is effective for measuring group velocity when dispersion effects are not pronounced. If there is strong dispersion, as evidenced by considerable spreading of echo B_2 relative to B_1, the phase-slope technique may be preferred to the cross-correlation technique. The phase-slope technique (**1**) is appropriate when dispersion effects cause velocity to be a strong function of ultrasonic frequency.

10.3 The velocity measurements obtained by this test method may be used as bases for materials characterization, that is, to characterize material microstructural factors such as density, pore fraction, grain size, or dispersed phases that influence mechanical properties (**7**).

10.4 Velocity measurements described herein can serve to determine material properties such as Young's modulus, Poisson's ratio, and acoustic impedance. Because ceramics have very low strain-to-fracture, velocity measurements provide an excellent nondestructive method for determining the moduli of brittle ceramics.

10.5 This test method can be used to generate velocity reference data for a variety of solids. Used with Test Method B311 or Test Method C373, this test method can be used to establish velocity calibration standards for fully dense and porous solids and thereby for indirect measurement of densities.

11. Keywords

11.1 ceramic composites; material microstructure; materials characterization; monolithic ceramics; nondestructive evaluation; polycrystalline metals; pulse-echo technique; structural composites; ultrasonics; ultrasonic velocity

REFERENCES

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(**3**) Roth, D. J., Stang, D. B., Swickard, S. M., and, DeGuire, M. R., "Review and Statistical Analysis of the Ultrasonic Velocity Method for Estimating the Porosity Fraction in Polycrystalline Materials," NASA TM 102501, 1990.

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