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Standard Guide for Acousto-Ultrasonic Assessment of Composites, Laminates, and Bonded Joints[1]

This standard is issued under the fixed designation E 1495; 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 guide explains the rationale and basic technology for the acousto-ultrasonic (AU) method. Guidelines are given for nondestructive evaluation (NDE) of flaws and physical characteristics that influence the mechanical properties and relative strength of composite structures (for example, filament-wound pressure vessels), adhesive bonds (for example, joints between metal plates), and interlaminar and fiber/matrix bonds in man-made composites and natural composites (for example, wood products).

1.2 This guide covers technical details and rules that must be observed to ensure reliable and reproducible quantitative AU assessments of laminates, composites, and bonded structures. The underlying principles, prototype apparatus, instrumentation, standardization, examination methods, and data analysis for such assessments are covered. Limitations of the AU method and guidelines for taking advantage of its capabilities are cited.

1.3 The objective of AU is to assess subtle flaws and associated strength variations in composite structures and bonded joints. Discontinuities such as large voids, disbonds, or extended lack of contact at interfaces can be assessed by other NDE methods such as conventional ultrasonics.

1.4 Additional information may be found in the publications cited in the list of references at the end of this guide. The referenced works provide background on research, applications, and various aspects of signal acquisition, processing, and interpretation.

1.5 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 543 Practice for Agencies Performing Nondestructive Testing[2]

E 1316 Terminology for Nondestructive Examinations[2]

2.2 *ASNT Standard*[3]*:*

ANSI/ASNT-CP-189 Standard for Qualification and Certification of Nondestructive Testing Personnel

Recommended Practice SNT-TC-1A Personnel Qualifications and Certification in Nondestructive Testing

2.3 *AIA Document:*

NAS-410 Certification and Qualification of Nondestructive Testing Personnel[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *acousto-ultrasonics (AU)*—a nondestructive examination method that uses induced stress waves to detect and assess the diffuse defect states, damage conditions, and variations of mechanical properties of an examination structure. The AU method combines aspects of acoustic emission (AE) signal analysis with ultrasonic materials characterization methods (Terminology E 1316).

3.1.2 Additional related definitions may be found in Terminology E 1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *stress wave factor (SWF)*—a generic measure of the relative energy loss (attenuation) or propagation efficiency of stress waves generated by the AU method. There are many ways to define and calculate the SWF. Several of these are described in Section 11 of this guide.

4. Summary of Guide

4.1 *General*—Two probes are attached to a sample in a send-receive configuration. One (a pulsed sending probe) is optimized for wave generation, while the other (a receiving

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[2] *Annual Book of ASTM Standards*, Vol 03.03.

[3] Available from American Society for Nondestructive Testing, 1711 Arlingate Plaza, P.O. Box 28518, Columbus, OH 43228-0518.

[4] Available from Aerospace Industries Association of America, Inc., 1250 Eye St., NW, Washington, DC 20005.

probe) is optimized for signal sensing. The probes are attached to the sample surface at normal incidence. The usual, and often most practical, configuration has piezoelectric probes, a sender and receiver, on the same side of the examination part **(1)**.[5] Measurements are performed by allowing ultrasonic stress waves to interact with a volume of material between the probes. The waves are modified by the material microstructure and morphology **(2)**.

4.2 *Principle*—The AU method measures the relative efficiency of stress wave propagation in a material. The dominant attribute measured is stress wave attenuation. Lower attenuation, a high SWF value, means better stress wave energy transmission for many composites and, therefore, better transmission and redistribution of dynamic strain energy. More efficient strain energy transfer and strain redistribution during loading or impact corresponds to increased strength and fracture resistance in composite structures and adhesive bonds. A lower SWF usually indicates regions in which strain energy is likely to concentrate and result in crack growth and fracture **(3)**.

4.3 *Structure Configuration Effects*—In monolithic plates and homogeneous composite slabs, the SWF will exhibit signal attenuation effects due to variations in microstructure, morphology, porosity, cure state, microcrack populations, etc. **(4)**. A lower SWF typically corresponds to regions of higher attenuation. In laminated structures or bonded joints, however, interfaces and bondlines can produce either lower or higher SWF values, depending on the bond quality **(5)**. Delaminated regions can produce higher SWF values because more energy is reflected or channeled to the receiving probe.

4.4 *In-Plane Measurements*—Offsetting probes enables the collection of stress wave reverberations that have traveled in-plane from sender to receiver. It is therefore possible to measure in-plane, mechanical property variations in principal load directions in fiber-reinforced laminates or adhesively bonded joints (that is, properties such as interlaminar shear strength and adhesive bond strength).

4.5 *Signal Collection Criterion*—With the AU method, instead of singling out specific echoes, all of the multiple reverberations, including signals from internal reflectors and scatterers, are collected and analyzed together. Even with pulse-echo or through-transmission configurations, all stress wave reflections and reverberations in a local volume of material are collected and evaluated, as in backscatter, forward-scatter, and diffuse field analysis.

4.6 *Wavelength Criterion*—In composite panels or bonded plates, the sender should produce wavelengths that are comparable to or less than the panel or plate thickness. Suitable wavelengths are those passed by the examination piece at frequencies equal to or greater than the sending probe center frequencies.

5. Significance and Use

5.1 *General*—Conventional ultrasonics should be considered first for the detection of overt flaws such as delaminations in composites. Thereafter, AU should be considered for composites that are proved to be free of major flaws or discontinuities. The AU method is intended almost exclusively for assessing the collective effects of dispersed defects and subcritical flaw populations. These are material aberrations that influence AU measurements and also underlie mechanical property variations, dynamic load response, and impact and fracture resistance.

5.2 *Specific Advantages*—The AU method can be used to evaluate composite laminate and bond quality using access to only one surface as, for example, the exterior surface of pressure vessels. It is unnecessary to utilize angle beam fixtures because the method can always be applied with probes at normal incidence. The method can be applied using dry coupling with elastomer pads attached to the probes, and there is no need to immerse the examination object in water.

5.3 *General Applications*—The AU method was devised to assess diffuse discontinuity populations and any associated changes of the mechanical properties of composites and composite-like materials. The AU method has been used to evaluate fiber-reinforced composites **(6)**, composite laminates **(7)**, filament-wound pressure vessels **(8)**, adhesive bonds **(9)**, paper and wood products **(10)**, and cable and rope **(11)**. The method has been shown to be particularly practical for assessing the strength of adhesively bonded joints. It has also been shown to be useful for assessing microporosity **(12)**, microcracking **(13)**, hydrothermal aging **(14)**, and damage produced by impacts **(15)** and fatigue **(16)**.

6. Basis of Application

6.1 *Personnel Qualification*

6.1.1 If specified in the contractual agreement, personnel performing examinations to this standard shall be qualified in accordance with a nationally recognized NDT personnel qualification practice or standard such as ANSI/ASNT-CP-189, SNT-TC-1A, NAS-410, or a similar document and certified by the employer or certifying agency, as applicable. The practice or standard used and its applicable revision shall be identified in the contractual agreement between the using parties.

6.2 *Qualification of Nondestructive Agencies*

6.2.1 If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as described in Practice E 543. The applicable edition of Practice E 543 shall be specified in the contractual agreement.

6.3 Proper application of the AU method requires the involvement of an NDE specialist to plan and guide the examination procedure. Knowledge of the principles of ultrasonic examination is required. Personnel applying AU should be experienced practitioners of conventional ultrasonic and acoustic emission examination and associated methods for signal acquisition, processing, and interpretation.

6.4 Particular emphasis should be placed on personnel having proficiency in computer signal processing and the use of digital methods for time and frequency domain signal analysis. Familiarity with ultrasonic spectrum analysis using digital Fourier transforms is mandatory. Spectral distribution, multiple regression, and pattern recognition analyses and adaptive learning procedures are important.

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[5] The boldface numbers in parentheses refer to the list of references at the end of this guide.

6.5 Application of the AU method also requires proficiency in developing and designing reference standards. The development of reference standards is needed for each type of material and configuration to be examined. Because AU measurements are relative and comparative, experimental examinations confirmed by destructive testing are needed to avoid ambiguities in the interpretation of results.

7. Limitations

7.1 *General*—The AU method possesses the limitations common to all ultrasonic methods that attempt to measure either absolute or relative attenuation. When instrument settings and probe configurations are optimized for AU, they are unsuitable for conventional ultrasonic flaw detection.

7.2 *Signal Reproducibility Factors*—The AU results may be affected adversely by the following factors: (*1*) improper selection of type and amount of couplant, (*2*) couplant thickness variations and bubbles, (*3*) specimen surface roughness and texture, (*4*) probe misalignment and insufficient pressure, (*5*) probe resonances and insufficient damping, and (*6*) insufficient instrument bandwidth.

8. Standardization

8.1 *Self-Standardization*—The sender and receiver probes can be used to verify each other. Deficiencies in the instrumentation and probe response become evident by comparing the results with the standard waveforms established previously for a reference item. Commercial ultrasonic probes and AE sensors respond to deformation (stress) waves in a complex fashion that involves both normal and in-plane displacements of the examination sample surface. Although it is possible to standardize such probes in an absolute sense, even sensors of the same design and specification should be treated as unique and definitely noninterchangeable.

8.2 *Stress Wave Factor Normalization*—Regardless of how the SWF is defined, it is practical to normalize it relative to some standard value, for example, the maximum value found for the optimum condition of a representative material sample or structure. This is appropriate where many nominally identical articles will be examined.

8.3 *Reference Standards*—Normalization of the SWF is the first step toward establishing a reference standard. The second step is to fabricate a set of samples exhibiting the full range of expected material conditions and flaw states. One of these samples should represent the optimum condition of the material. This procedure should be followed by the development of benchmark structures that can be used as comparative standards.

9. System Configuration

9.1 *Standard Configuration*—Four possible AU probe configurations are shown in Fig. 1. With the probes on the same side of a panel, examination proceeds by holding the probes in a fixture and moving them as a unit to cover the examined area. For zero offset between probes, the configuration reduces to either the pulse-echo or through-transmission mode, as shown in Fig. 1 (b) and (d) respectively. The prototype apparatus depicted in Fig. 2 illustrates the essential features of a standard configuration.

9.2 *Probes*—Two classes of piezoelectric probes are appropriate: (*1*) resonant and non-resonant AE sensors, and (*2*) damped broadband ultrasonic probes. Resonant AE sensors have more sensitivity, but the signals transmitted by the test piece may be of sufficient strength such that sensitivity is not a problem. One reason for avoiding resonant sensors is that they have ringdown characteristics that may be difficult to separate from the multiple reflections transmitted by the examination sample.

9.2.1 *Probe Bandwidth*—Non-resonant AE sensors have a flatter frequency response curve than resonant sensors. This response characteristic should be exploited in AU because it would render a truer signal over a wider bandwidth. Another

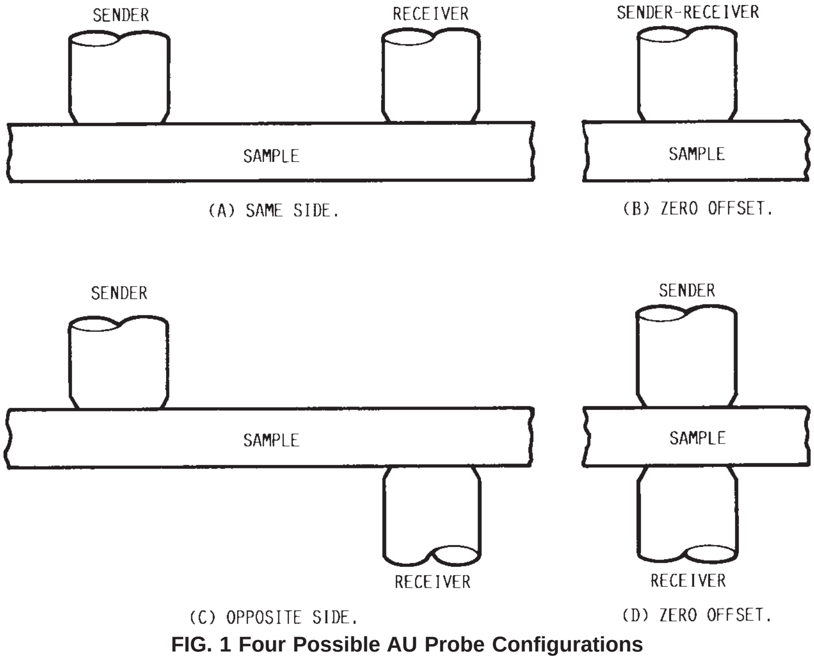


FIG. 1 Four Possible AU Probe Configurations

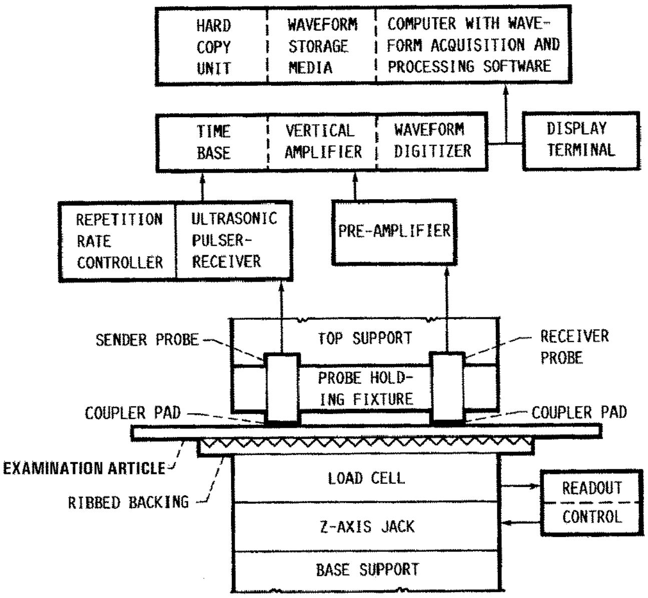


FIG. 2 Diagram of Apparatus and Instrumentation Used for Laboratory Application of AU

approach is to use the bandwidth response of damped broadband ultrasonic probes. Good results can be obtained with broadband ultrasonic probes working as both senders and receivers. For many fiber-reinforced composites, broadband probe pairs with center frequencies ranging from 0.5 to 5 MHz prove useful, for example, send-receive pairs of 2.25 MHz damped probes. Broadband commercial piezoelectric probes will produce satisfactory AU results for many composite structures.

9.2.2 *Probe Combinations*—Combinations of damped broadband ultrasonic and AE sensors can be used. The choice depends on the nature of the material being examined. The material may require the use of a broadband ultrasonic sender and a resonant AE sensor as receiver. A broadband sender would cover frequencies potentially passed by the examination sample, while the receiving sensor would be tuned to a particular frequency determined to be the most appropriate for assessing a particular property.

9.2.3 *Probe Facing*—To improve coupling, it is useful to machine the epoxy face or wearplate of the probes so that the contact area is reduced to a fraction of 1 cm.^{2} To reduce the area of contact, it also helps to bond waveguides to the faces of the probes. Waveguides should consist of truncated solid cones with their wide ends bonded to probe faces.

9.2.4 *Reverberation Effects*—Reverberations in faceplates and facing attachments can mimic probe ringdown. The reverberations can be quite strong if the acoustic impedances between layers (wearplate, facing, and examination materials) are significantly mismatched. The effect will appear in waveforms as additional ringdown and in spectra as spurious interference peaks. Since these effects do not represent the examination sample, care should be taken to avoid or eliminate them during signal analysis.

9.2.5 *Probe Fixturing*—The probes shown in Fig. 2 are held firmly in a support fixture so that a predetermined spacing is maintained. The fixture is designed to avert crosstalk between probes. It must be rigid enough to assure that the probes can be pressed firmly, as a unit, against the examination piece to optimize coupling pressure.

9.2.6 *Probe Spacing*—Probe spacing is determined by the following factors: (*1*) wave attenuation within the examination sample, (*2*) probe bandwidth and sensitivity, (*3*) sample thickness and shape, (*4*) diameter of the probes, and (*5*) spatial resolution required in the scan images. Because the objective of AU is not the generation of high-resolution images of minute flaws, probe spacing may be quite large, typically several centimetres from probe centerline to centerline. The objective should be to interrogate a representative volume of material for a given probe spacing.

9.2.7 *Probe Alignment*—The AU method should be accomplished with probes at normal incidence because the method is particularly sensitive to probe alignment and associated coupling variations. There is no need for oblique angle probes. In conventional ultrasonics, the chief reason for oblique incidence is to produce shear waves. Shear waves will arise naturally with the AU approach due to beam spread and mode conversions of reflected waves.

9.3 *Coupling Methods*—When a fluid medium is used for coupling probes to a surface, a gel type is preferred. A fluid couplant should (*1*) provide good acoustic coupling over the desired frequency range, (*2*) be chemically inert, (*3*) be easy to remove, (*4*) be consistent from batch to batch, and (*5*) maintain consistent properties during the period and at the temperatures used.

9.3.1 *Couplant Application*—Particular attention should be paid to the application of fluid couplant to probes. Control should be exercised over the following factors: (*1*) amount of couplant applied, (*2*) avoidance of air bubbles, (*3*) assurance of a thin and uniform film, and (*4*) avoidance of excess couplant. The amount of couplant should not be such that it overflows at the edge of the probe face, thereby absorbing energy and altering results.

9.3.2 *Coupling Pressure*—Laboratory experiments have shown that an optimum coupling pressure exists. When the pressure applied to the probes is small, the received signal will also be small. As the pressure is increased, a definite increase in signal strength will occur until the pressure is optimal for the probe-couplant-material combination. Any further increase in pressure will have no significant effect on the signals.

9.3.3 *Dry Coupling*—The need for dry, soft coupling occurs in instances in which it is necessary to either deal with rough surfaces or avoid the infusion of fluid into porous materials. Efficient coupling can be achieved with elastomer pads bonded to the probe face. When pressed against the examination surface, the elastomer will conform to any surface roughness or texture providing good coupling.

9.3.4 *Example*—For the laboratory prototype apparatus depicted in Fig. 2, the force applied was roughly 12 N (2.7 lb) at a pressure of 120 000 Pa (18 psi) per probe over the area of the silicon rubber pads. The uncompressed elastomer pad thickness was approximately 1 mm, and the contact area was approximately 0.2 cm^2. The pads did not cover the entire probe face, so that the contact area with the examination piece was small enough to ensure uniform pressure.

9.4 *Examination Sample*—Because of the sensitivity of the AU method, seemingly minor variations in material conditions, examination setup, and execution can alter results. This parallels the situation in AE examination, in which material and examination condition variations can have pronounced effects.

9.4.1 *Surface Roughness*—Composites may have rough or textured surfaces (as in autoclaved and filament-wound structures). Superficial factors can imprint on the received signal. Substrate variations can obscure the effects of volume variations. Overcoming these surface and substrate effects may require trials with various frequency bandpasses to isolate and eliminate these variables.

9.4.2 *Sample Support*—In the laboratory setup shown in Fig. 2, the examination article is clamped between the probes and a backing consisting of a ribbed, hard, rubber pad. Ribs minimize contact and substantially reduce the leakage of ultrasonic energy from the back surface. This prevents any short circuiting of the examination piece through the backing support. Special backing may not be necessary in field applications, but the examination article must be held in fixturing that assures firm and precise probe contact.

9.4.3 *Sample Geometry Effects*—Sample geometry effects will be more significant for small examination articles. Even for large composite structures, cross-section changes or edges near the probes will affect signals reaching the receiver. Uniform size, shape, and thickness measurements shared by the examination articles help ensure that the signals truly characterize material anomalies. The AU method requires constant material thickness and uniformity for comparative measurements.

9.5 *Mapping and Scanning*—The mapping of material variations requires scanning by lifting and recoupling the probes or using rolling probes. Water jet methods can scan large areas and curved surfaces readily.

9.5.1 *Mapping Methods*—Single AU measurements on an examination sample should not be relied on. It is advisable to make a number of overlapping measurements to characterize an examination sample. This can be systematized by defining a grid over an area on an examination sample. It is also useful to make AU measurements in several directions. There is much to be gained from mapping the SWF relative to fiber orientation in fiber-reinforced composites.

9.5.2 *Rolling Coupling*—Dry or fluid-coupled mapping can be accomplished by probes stationed in the hubs of elastomer-rimmed wheels. Elastomer wheeled probes are commercially available. Trials should be conducted with the type of composite and defect population being examined to ensure that their frequency range or bandwidth sensitivity falls within that required for the best results. The alignment and footprint of wheeled probes should be optimized for the examination material and conditions.

9.5.3 *Water Jet Coupling*—The AU method has been applied successfully to contoured and curved surfaces using probes encased in a squirter fixture **(8)**. Water jets couple the probes to a part and allow free scan movement. Water jet probe fixtures are commercially available and are currently used for conventional ultrasonic scanning. A dual probe fixture with two water jets side by side can be used for AU, as in the standard single-side configuration.

9.6 *Instrumentation*—Representative electronic instrumentation for AU signal generation, acquisition, and processing is depicted in Fig. 2. An ultrasonic pulser is used to excite the sending probe periodically. The pulser repetition rate is set so that signals reaching the receiver probe die out before the next pulse. The pulser triggers the time base to synchronize the waveform digitizer oscilloscope sweep with the receiver probe output.

9.6.1 *Signal Processing*—Analog or semi-digital processing of signals can be used to monitor variations of the material sample being examined. This can be accomplished by methods developed for AE, for example, the use of a ringdown count or rms voltage to evaluate changes in the received signal. With digital acquisition, storage, and display, each signal should be spectrum analyzed and stored along with data concerning the examination piece and coordinates of each AU measurement.

9.6.2 *Bandwidth*—Commercial ultrasonic pulsers and AE instrumentation can be adapted for AU applications. However, many composites and bonded joints will require interrogation at frequencies higher than those commonly used in AE. In these cases, instruments require a bandwidth greater than that typical for current AE systems. These applications may require bandwidths of up to 5 MHz. Nevertheless, for many types of composites and composite-like materials (that is, large, coarse textured structures), frequencies down to tens of kHz may be appropriate.

9.6.3 *Pulser*—Commercial ultrasonic pulsers are appropriate for AU. Pulser circuits provide appropriate excitation voltages and selections of rise times, pulse durations, and repetition rates. Ultrasonic pulsers are used in AU practice to drive either damped probes or undamped resonant AE sensors. It is preferable to use pulsers that can generate broadband signals from tens of kHz to several MHz.

9.6.4 *Preamplification*—The receiver probe output should be preamplified before entering the vertical amplifier of an oscilloscope or digitizer. This is to overcome the electronic noise associated with the antenna effect of the cable between the AU sensor and oscilloscope. The AE preamplifiers with either 40 or 60-dB gain are appropriate for this purpose. The AE preamplifiers are usually powered by d-c voltage from the main AE electronic unit. Stand-alone battery-powered units are preferable because they have less electronic noise.

9.6.5 *Preamplifier Cables*—The cable that connects the preamplifier to the AU sensor is normally coaxial. Unless the cable is perfectly shielded, it can act as an antenna and pick up ambient electromagnetic radiation. This electronic noise can be kept low by either using a short cable (for example, 1-m long) or making the preamplifier integral with the probe. A standard cable length is desirable for preamplifiers, and the cable should be terminated with its own characteristic impedance for maximum power transfer.

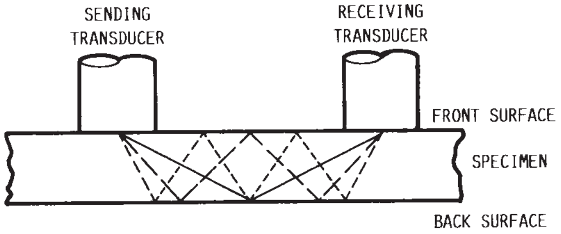
9.6.6 *Digitizer*—Programmable digitizing oscilloscopes are ideal for signal acquisition. The preamplifier output is fed into the vertical amplifier while the synchronization signal from the pulser repetition control is fed into the time base. Contemporary digitizers can perform essentially real-time operations. They have a wide signal processing repertoire that includes peak voltage, rms power, and spectrum analysis. These capabilities can be used for evaluating AU signals in accordance with the procedures described in Section 11.

9.6.7 *Data Processor*—Personal computers modified for AU signal processing are available for use with digitizing oscilloscopes. With general purpose interface boards, personal computers can be used to collect and store AU signals and auxiliary data such as current coordinates of probe fixtures relative to test samples. Specialized software should be developed for utilizing advanced methods for signal analysis, such as those discussed in Section 12.

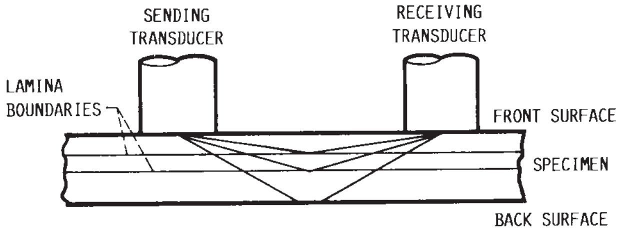
10. Signal Characteristics

10.1 *Nature of AU Signals*—A simplified account of AU signal generation in a flat monolithic plate follows. The probes are represented by a point sender and point receiver, as shown in Fig. 3. The point sender emits pressure waves (P-waves) uniformly into the plate. For any nearby arbitrary point receiver, it is possible to trace a P-wave ray that has been reflected from the back surface of the plate. Similarly, it is possible to trace a second ray that arrives at the point receiver after it has been mode-converted to a shear wave (S-wave). More P-waves arrive after reflections from the back and front surfaces of the plate. Additional reflected S-waves will also arrive at later times and add to the resultant signal sensed by the point receiver **(17)**.

10.2 *Signal Development*—The resultant waveform at the point receiver will consist of the superposition of numerous separate wavelets. The resultant waveform consists of several generations of P- and S-waves. Angles of reflection wavespeeds, and attenuation of the wavelets, are governed by elastic moduli and attenuation properties of the material. The resultant waveform at the point receiver will have an envelope and other characteristics peculiar to the material properties and boundaries.



(A) FIRST, SECOND, AND THIRD ORDER LONGITUDINAL (P-WAVE) RAY PATHS.



(B) FIRST ORDER LONGITUDINAL (P-WAVE) RAY PATHS IN LAMINATED SOLID.

FIG. 3 Point Source-Receiver Ray Traces Illustrating the Development of AU Signals from Reflected Waves in a Monolithic and Laminated Solid

10.3 *Waveform Envelope*—The AU waveform envelope is initially shaped by small oscillations that precede a series of increasing oscillations that reach a maximum, as shown in Fig. 4. These initial oscillations arise from the first direct reflections from the back surface (Fig. 3). The initial oscillations are small because they arise from reflections at obtuse angles, as in Fig. 4 (a). Following the maximum oscillation of a waveform, subsequent oscillations diminish in amplitude. These trailing ringdown oscillations arise from reflections that are attenuated over longer multiple reflection paths.

10.4 *Variables Affecting Signals*—The AU signals are influenced by a number of material parameters. These include elastic moduli, density, reflection and attenuation coefficients, longitudinal and shear wave velocities, texture, microstructure, and, of course, boundary conditions (surfaces, edges, curvatures, etc.). The presence and nature of diffuse microflaw populations and other flaw states can be inferred from their effects on the velocity and attenuation of AU signals.

11. Signal Quantification

11.1 *Stress Wave Factor*—The SWF concept was developed to quantify signals generated by the AU method. This section provides various definitions of SWF. The simplest definitions, based on AE peak voltage or ringdown count methods, often correlate quite well with particular flaw conditions. Examples of empirically viable approaches for calculating SWF are given below.

11.2 *Peak Voltage SWF Method*—The peak voltage in most materials changes inversely with attenuation and affords an effective basis for defining SWF. Using either analog or digital peak detection, SWF may be defined as follows:

$$\text{peak voltage} = V_{\max} \tag{1}$$

where:

$V_{\max}$ = maximum (peak-to-peak) voltage oscillation.

This SWF formulation assumes that the peak voltage varies with the flaw state of the material being examined.

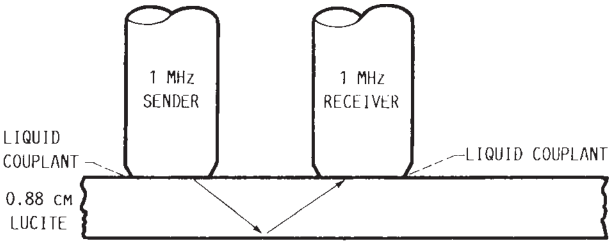
11.3 The peak voltage definition of SWF has proven useful for assessing microcrack damage accumulation in composite laminates subjected to tensile loading. A related definition equates SWF to the integral of voltage squared, V^2, taken over the duration of the AU signal. This later definition appears to be sensitive to initial stages of damage accumulation.

11.4 *Ringdown SWF Method*—The AU signals frequently resemble AE burst waveforms that decay exponentially. Accordingly, SWF can be quantified as a ringdown count. Using AE methodology and a ringdown count totalizer, SWF can be defined as follows:

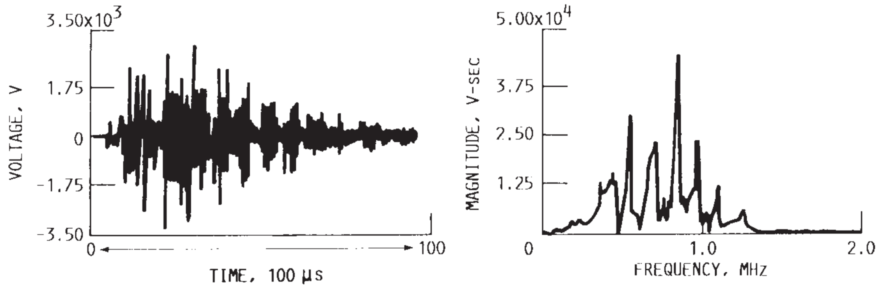
$$\text{ringdown count} = PRC \tag{2}$$

where:

P = pulser repetition rate,
R = totalizer reset time, and
C = ringdown count per waveform.



(A) LATERAL TRANSMISSION PROBES.



(B) MULTIPLE REFLECTION WAVEFORM. (C) SPECTRUM OF TRANSMITTED WAVEFORM.

FIG. 4 Standard (Same-Side) AU Probe Configuration and Characteristic Waveform and Spectrum for a Monolithic Plastic Plate

The repetition rate is set so that each signal rings down below the threshold voltage before a new signal starts. The reset time allows for averaging a predetermined number of signals into the total count display, such as that which would be shown by an AE totalizer. Defined in this way, SWF is inversely proportional to relative attenuation predicated on the number of oscillations that occur before the signal decays below the threshold.

11.5 The ringdown definition of SWF assumes that the waveform always has a monotonic decay envelope; it is likely to be inappropriate if the waveform is multimodal and has a non-monotonic decay envelope, for example, as in Fig. 4. Moreover, the ringdown waveform may include probe ringdown if resonant or undamped probes are used.

11.6 The earliest work with AU used the ringdown definition for SWF and produced good correlations with ultimate strength and interlaminar strength in fiber-reinforced epoxy composite panels. The ringdown count formulation of SWF has become the definition against which new definitions are compared. The ringdown definition was merely the first but still useful quantification of the SWF.

11.7 *Weighted Ringdown SWF Method*—An alternative to the previously described ringdown definition of SWF is a refinement that accounts for the amplitude of each ringdown oscillation. This formulation for SWF is defined as a sum of threshold voltages, V_i, that increase from the noise level V_o to the peak amplitude by a fixed voltage increment:

$$\text{weighted ringdown} = \sum_{i}^{p} V_i(C_i - C_{i+1}) \quad (3)$$

where:

V_i and C_i = threshold voltage and number of oscillation counts at the i-th level, respectively, and

V_p = peak amplitude of the waveform.

This is a better quantification of SWF than a simple ringdown count. As with the previous definitions of SWF, the measurement will be inversely proportional to relative attenuation changes in the examination material.

11.8 The weighted ringdown count has been applied to the assessment of impact damage in fiber composites and strength variations of adhesively bonded joints. Correlations between the weighted ringdown count SWF and adhesive bond degradation can be improved by frequency filtering or spectral partitioning. This involves taking the Fourier transforms of original waveforms and zeroing out digitally all but a narrow portion of the spectrum. The reduced spectrum is then reverse transformed to obtain a reduced waveform that exhibits a smaller frequency range. This range can be determined by frequency partitioning and regression analysis, which is discussed in this section. Once the optimum range is determined, a weighted ringdown count is calculated for the reduced waveform **(18)**.

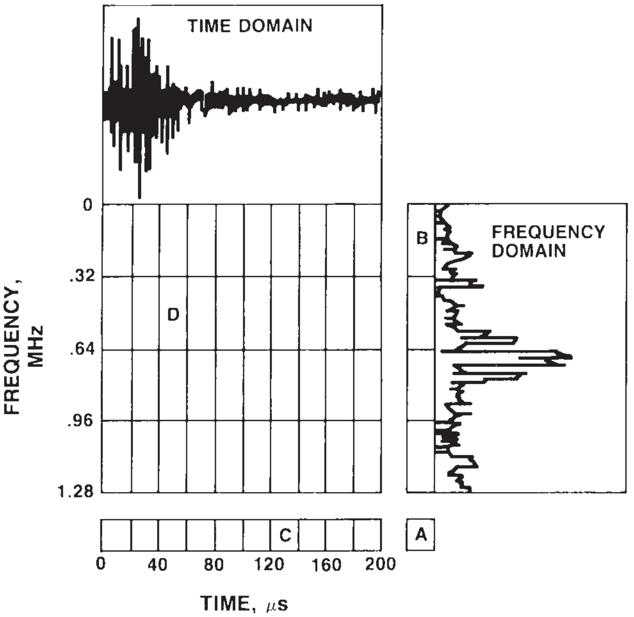
11.9 *Energy Integral SWF Method*—The relative energy of AU signals can be defined as follows:

$$\text{energy integral} = \int_{t_1}^{t_2} [v(t)]^2 dt \quad (4)$$

over the interval t_1 to t_2, where $v(t)$ = voltage. By producing the Fourier transform of the signal, a frequency domain definition of SWF can be given in terms of the power spectrum:

$$\text{power spectrum} = \int_{f_1}^{f_2} [s(f)]^2 df \quad (5)$$

over the frequency interval f_1 to f_2, where $s(f)$ = spectral distribution function for the waveform. The SWF definitions given in (Eq 4) and (5) are equivalent if applied to the entire waveform or spectrum. The power spectrum definition of SWF of (Eq 5) has been found to be a sensitive indicator of the development of fatigue damage in graphite/epoxy composite laminates.



BLOCK "A" IS FOR THE TOTAL WAVEFORM OR SPECTRUM.
BLOCK "B" IS FOR THE FREQUENCY INTERVAL 0 TO 0.3 MHz.
BLOCK "C" IS FOR THE TIME INTERVAL 120 TO 140 μs.
BLOCK "D" IS FOR THE INTERVAL 0.3 TO 0.6 MHz, 40 TO 60 μs.

FIG. 5 Diagram of Waveform Partitioning Scheme for Regression Analysis Method for Determining Optimum SWF for Correlating with Material Properties. Partition Blocks are Filled with Coefficients Obtained by Regressing SWF Values Within the Time and Frequency Intervals Shown Against the Material Property of Current Interest. Blocks with the Highest Values Indicate Time or Frequency Intervals that Correlate Most Strongly with the Material Property

11.10 Unlike the case with the SWF definitions in (Eq 2) and (Eq 3), there is no need to specify a threshold voltage with the energy integral methods. However, it is necessary to specify the time and frequency intervals of the integrals in (Eq 4) and (Eq 5). Consideration should therefore be given to empirical selection of the time or frequency intervals that correlate best with the particular flaw states or material properties of interest.

11.11 *Partitioning Method*—Regression analysis can be used to determine whether particular time or frequency partitions produce strong correlations with specific defect states. The rationale is that only certain parts of waveforms or spectra contain relevant information. A scheme for waveform and spectrum partitioning is illustrated in Fig. 5 **(6)**.

12. Interpretation of Results

12.1 *General*—The fundamental quantity measured in AU is relative attenuation. This can be accomplished using the SWF quantification methods described. However, signal interpretation may require methods such as neural network and pattern recognition **(19)** in association with spectral moments analysis **(20)**.

12.2 *Neural Network Method*—Pattern recognition, feature extraction, and statistical classification methodologies should be applied. By using training samples, key signal patterns can be identified and associated with specific flaw conditions.

12.3 *Spectral Moments Method*—The AU signals usually exhibit characteristic spectra associated with different flaw states in a material. Relative changes in spectra suggest the application of homomorphic and spectral moment analyses.

13. Keywords

13.1 acoustic emission; acousto-ultrasonics; bonded joints; composites; laminates; materials characterization; mechanical properties assessment; nondestructive evaluation; nondestructive testing; stress wave factor; ultrasonic attenuation

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