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Comparison of Dynamic Methods for Determining Elastic Property Measurements of Solid Materials

by Raymond Brennan, Michael Golt, and Mathew Ivill

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14. ABSTRACT

Nondestructive evaluation techniques such as ultrasound point analysis (UPA), resonant ultrasound spectroscopy (RUS), and impulse excitation (IE) have been commonly used for determination of elastic properties for various materials and components. These dynamic methods, which are categorized into pulse techniques for measuring transit time of an ultrasonic pulse (UPA), and resonance techniques that set samples into mechanical vibration (RUS and IE), have been extensively applied for evaluation of armor materials, including ceramics. Dynamic testing methods such as these are highly suited for brittle materials that cannot support large deformation strains before failure, making them particularly attractive for the characterization of hard ceramics. All three of these methods are currently available in the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory's (ARL's) Ceramic and Transparent Materials Branch within the Materials and Manufacturing Science Division for determining the elastic properties and speed of sound in materials. The purpose of this report is to provide a brief overview of these techniques, a summary of specimen requirements, and a comparison of pros and cons to determine which technique should be selected for a given application.

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1. Introduction

Nondestructive evaluation (NDE) techniques such as ultrasound point analysis (UPA), resonant ultrasound spectroscopy (RUS), and impulse excitation (IE) have been commonly used for determination of elastic properties for various materials and components. These dynamic methods, which are categorized into pulse techniques for measuring transit time of an ultrasonic pulse (UPA), and resonance techniques that set samples into mechanical vibration (RUS and IE), have been extensively applied for evaluation of armor materials, including ceramics.[1,2] Dynamic testing methods such as these are highly suited for brittle materials that cannot support large deformation strains before failure, making them particularly attractive for the characterization of hard ceramics. All three of these methods are currently available in the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory's (ARL's) Ceramic and Transparent Materials Branch within the Materials and Manufacturing Science Division for determining the elastic properties and speed of sound in materials. The purpose of this report is to provide a brief overview of these techniques, a summary of specimen requirements, and a comparison of pros and cons to determine which technique should be selected for a given application.

2. Ultrasound Point Analysis (UPA)

UPA is conducted by using ultrasonic transducers, which transmit and receive acoustic waves into the test specimen. The two major types of acoustic waves include longitudinal and shear waves (Fig. 1). For longitudinal (compressional) waves, acoustic vibrations—or oscillations—occur in the direction of propagation.[3] In solid bodies, shear (transverse) waves are also present, in which the particles oscillate at right angles to the direction of propagation.[3] Acoustic wave interaction with a bulk material is characterized by the volume of material displaced against the elastic constraints of its bonds. Since the ease of wave propagation is a function of density (how much material must be moved) and elastic constraint (how difficult it is to move the material), these interactions can be used to calculate material and elastic properties within a specimen.[4]

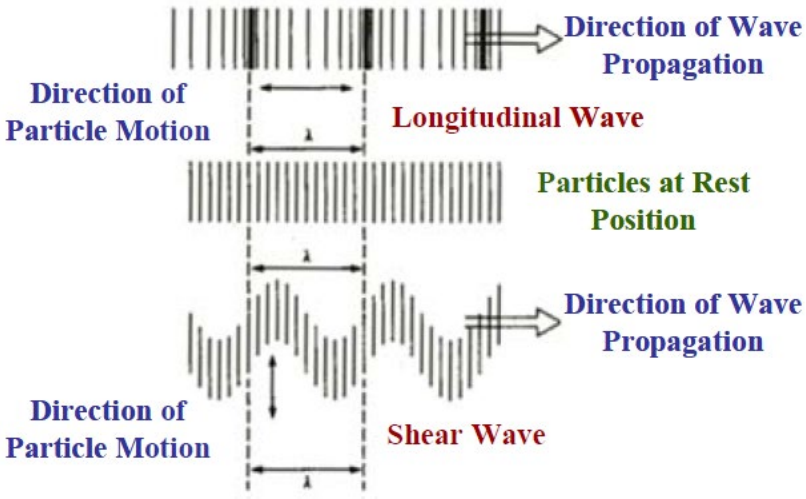

Fig. 1 Schematics of longitudinal and shear acoustic waves showing direction of wave propagation differences

In an ultrasound system, a pulser–receiver unit sends an initial electrical pulse to an ultrasonic transducer and the piezoelectric crystal in the transducer converts the pulse into longitudinal and shear acoustic waves. The waves are sent into the material that is being analyzed and either transmit, reflect, or scatter energy, depending on the impedance differences between acoustic boundaries.[5] For a larger difference in acoustic impedance, more energy is reflected or scattered, and less energy is transmitted into the material. The scattered and reflected signals from the material are received by the same transducer in pulse–echo mode and the piezoelectric crystal converts the signals back into electrical waves, which are sent to the receiver of the pulser–receiver to amplify them. The amplified signals are displayed as a voltage versus time trace on an oscilloscope, which is used to identify the trigger signal from the transducer, the reflected signal from the top surface of the sample, the reflected signal from the bottom surface of the sample, and additional reflection signals and echoes. This set of signals is referred to as an amplitude-scan, or A-scan.[5]

Time-of-flight (TOF) of a specimen is defined as the transit time between the top surface reflection and the bottom surface reflection. By using a simple relationship of distance equals rate times time, where time is TOF and distance is the known thickness (t) of the sample, longitudinal (c_l) and shear (c_s) wave velocities can be determined using the following equations[5]:

$$c_l = 2t / TOF_l \quad (1)$$

$$c_s = 2t / TOF_s \quad (2)$$

The factor of two is added for pulse–echo configuration as a round-trip time of travel, since the same transducer is used for both transmitting and receiving the acoustic waves. Material velocities (that indicate speed of acoustic wave travel through a material), acoustic impedance values (material properties that determine acoustic mismatch), and bulk densities of common armor, defect, and coupling medium materials can be found in Table 1. If the density (ρ) of the specimen is known, the acoustic impedance (Z) can also be determined from Eq. 3[5]:

$$Z = \rho\, c_l \tag{3}$$

Table 1 Acoustic impedance, material velocity, and density values for common ceramics, defects, and acoustic mediums

Ceramic materials	Density (g/cm^3)	Longitudinal velocity (m/s)	Acoustic impedance ($\times 10^5$ g/cm^2 s)
Air	…	330	0.0004
Water	1.00	1480	1.48
SiC (sintered)	3.18	12,000	37.5
SiC (hot pressed)	3.22	12,200	39.0
Al_2O_3 (sintered)	3.98	10,600	43.0
B_4C (sintered)	2.50	14,500	36.2
TiB_2 (sintered)	4.50	11,400	51.3
WC (sintered)	15.8	9500	114.0
Al_2O_3 (green)	…	1600	2.4
WC (green)	…	1400	2.8
Carbon	1.47	2250	6.3
Iron	7.69	5900	45.5

Note: SiC = silicon carbide, Al_2O_3 = alumina, B_4C = boron carbide, TiB_2 = titanium diboride, WC = tungsten carbide.

Assuming isotropic conditions, Poisson's ratio, ν, can be calculated from c_l and c_s, using Eq. 4[6]:

$$\nu = [1 - 2\,(c_s / c_l)^2] / [2 - 2\,(c_s / c_l)^2] \tag{4}$$

Elastic, or Young's modulus, E, shear modulus, G, and bulk modulus, K, can also be calculated by Eqs. 5–7[6]:

$$E = [(c_l)^2(\rho)(1-2\nu)(1+\nu)] / [g(1-\nu)] \tag{5}$$

$$G = (c_s)^2\,(\rho) \tag{6}$$

$$K = E / [3\,(1 - 2\nu)] \tag{7}$$

These equations assume isotropic elastic properties. Using this technique, TOF values can be used to calculate material velocities and elastic properties in various materials, including armor ceramics.

UPA can be conducted on an armor component at a single location by using ultrasonic transducers to collect A-scan data. Longitudinal and shear wave transducers can be used to measure longitudinal TOF and shear TOF values, respectively. The aforementioned equations can then be used to calculate corresponding longitudinal velocity, shear velocity, acoustic impedance, Poisson's ratio, elastic modulus, shear modulus, and bulk modulus values.

When conducting UPA, bulk components with parallel surfaces and minimal surface roughness are ideal. High-density components with minimal surface or bulk defects are also advantageous for providing the best ultrasound results. From a materials standpoint, ceramics and metals that generally exhibit high acoustic impedance and material velocity values are also among the most favorable for ultrasound analysis. That being said, UPA is a very flexible method for evaluating numerous materials, whether or not they meet these idealized conditions. As long as the top and the bottom of the sample can be accessed, the surface roughness is not severe, and the reflected signals can be resolved, TOF values can typically be determined and related properties calculated. This has been demonstrated on larger, thicker materials with curved or rough surfaces.[7] It has also been successfully applied to lower-acoustic impedance materials, such as polymers.[8] One option for increasing the flexibility of the technique is by using transducers of varying frequencies, with lower-frequency transducers typically more effective for thicker samples (as the depth of penetration is not affected as much by attenuation), or those with rough or curved surfaces. In contrast, higher-frequency transducers are more effective for generating sharper peaks for resolving signals and providing more accurate data, especially in high-density, high-acoustic impedance bulk samples such as armor ceramics.

3. Resonant Ultrasound Spectroscopy (RUS)

Every object has a set of characteristic resonance, or free oscillation frequencies, determined by its geometry, size, density, and elastic properties over which its mechanical strain is maximized. When a free object is momentarily struck by a brief impulse, it will vibrate and resonate momentarily at multiple, discrete characteristic frequencies. An example is a tuning fork. If a free object is presented in an acoustic wave with a frequency that is not characteristic, it will respond with little mechanical strain and is otherwise passive. However, if the object experiences an acoustic frequency specific to one of its characteristic frequencies, it will

respond actively with large strains. A well-known example is the high-strain resonance and eventual destruction of a wine glass by an opera singer's voice. As the name implies, RUS operates on the resonance of a sample within the vibrations caused by acoustic waves. During a RUS measurement, the sample is vibrated in its entirety over a range of swept frequencies by a drive transducer, and one or many receiver transducers measure the resulting amplitude of strain provided by the object at each frequency. The result is a spectrum where resonance frequencies are recorded with high-amplitude signals and all other swept frequencies contain minimal, or baseline, signals. Analytical or numerical forward models can predict resonance frequencies given the geometry, size, density, and elastic properties. The inverse problem is then solved, often through nonlinear least-squares optimization, where candidate elastic properties are iterated into the forward model to find the properties that best fit multiples of the measured resonance frequencies. Hence, the bulk elastic properties of a sample can be found from the RUS-measured resonance frequencies when the geometry, size, and density are known.

Most sample volumes for RUS are within the range of a millimeter cubed to as large as tens of centimeters. Samples must have a combination of geometry, size, density, and elastic properties that will produce at least a couple of resonance points within the frequency range of the transducers—roughly 1 kHz to several MHz. In some industries, RUS is used as a quality control tool where a sample's resonance is compared with an expected resonance to determine if the combination of geometry, size, density, and elastic properties are within an acceptable tolerance. In this application, the properties are not necessarily determined through model fitting. When, however, the properties are sought, the geometry, size, and density must be known as accurately as possible to effectively solve the inverse problem. Often, well-machined and simple geometries (sphere, cylinder, rectangular parallelepiped) are used to minimize errors in measuring the geometry. In addition, parameterized analytical forward models have already been developed for simple geometries and are usually deployed on RUS-attached PCs. For complex geometries, finite-element analysis (FEA) can be used to solve for an object's resonance when given accurate dimensions or a 3-D scan of the object. The optimization algorithm will iterate the FEA model through candidate elastic properties to find the combination that best fits the measured resonance peak locations. After a spectrum is recorded, the user must manually identify and select the location of each resonance peak. These selections are then given to an optimization algorithm to solve the inverse problem. At least two of the elastic properties (Young's/bulk/shear modulus and Poisson's ratio) are required, and good initial guesses of the specimen's properties are needed to avoid finding an inaccurate local minima combination of the values.

The two-point measurement of a 3-cm-long alumina dumbbell compression specimen in a Magnaflux Quasar RUSpec system is shown in Fig. 2. The specimen is positioned on its edge to maximize the signal and ensure that the test specimen is a free body. In this configuration, one transducer is used to generate acoustic vibrations while the other transducer receives the response. This Magnaflux Quasar RUSpec system can accommodate a second receiver transducer that can be arranged with the other transducers as a tripod to support and measure larger objects. Transducer placement can play an important role in obtaining resonance peaks with a high signal-to-noise ratio. Resonance is expressed in different modes of displacement. It is possible that the displacement of some modes is in a plane or location on the specimen that impinges minimally on the receiving transducer; thus, the resonance at that frequency might be missed. An FEA simulation will illustrate the resonance frequencies and modes and can inform optimal transducer placement.

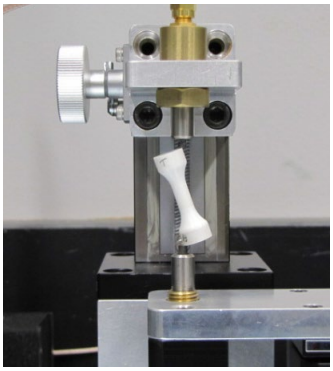

Fig. 2 Alumina dumbbell sample between top and bottom transducers of the Magnaflux Quasar RUSpec system. The dumbbell in this figure is 3 cm long.

The spectrum collected for the 3-cm-long alumina dumbbell specimen is shown in Fig. 3.[9] The sharp peaks in the spectrum are the resonance frequencies. FEA simulations of the locations and resonance modes of the specimen are overlaid. This specimen undergoes several different modes—from the lowest flexural mode to the lowest torsional mode, to the first flexural overtone mode, to the lowest extensional mode—followed by overtone modes that will continue into higher frequencies. In some cases, the resonance mode can be degenerated and a disruption in the axial symmetry due to a machining flaw or inhomogeneity in the volume will cause the peak to bifurcate. Care must be taken to properly assign the bifurcated peak locations to a single resonance point. Refer to the cited reviews[10,11] for more information on RUS, its applications, and limitations.

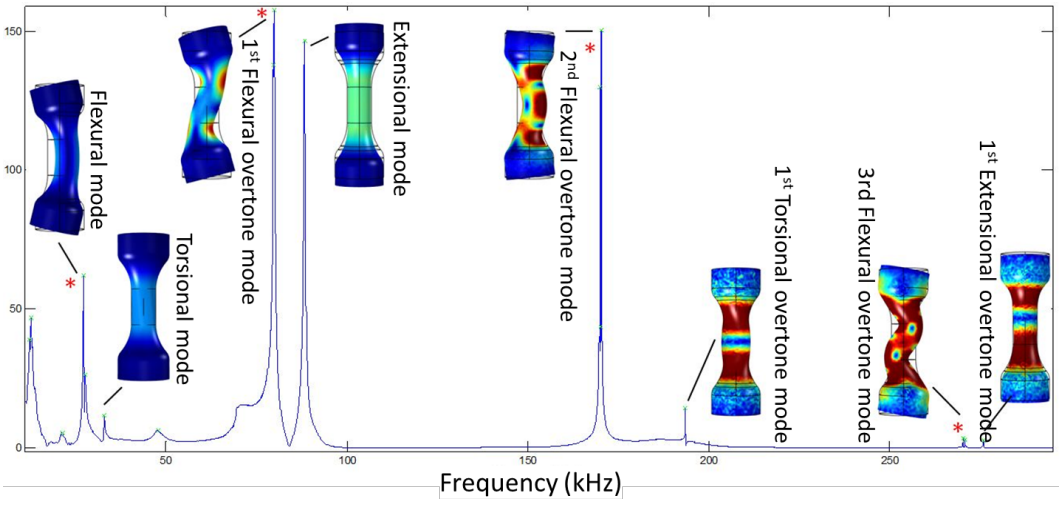

Fig. 3 Measured resonance spectrum for the alumina dumbbell sample of Fig. 2 overlaid with the modeled vibrating modes. Large asterisks identify the degenerate bending frequencies that diverge if the axial symmetry is disrupted by inhomogeneities or machining flaws. Color indicates von Mises stress.

4. Impulse Excitation (IE)

The IE technique is a relatively simple, quick, and nondestructive method to determine the elastic properties of homogenous materials. It relies on measuring the vibrational resonant frequencies of a freely vibrating (unconstrained and unloaded) sample. These resonant frequencies carry important information regarding physical properties and depend upon the material elastic properties, as well as the mass and geometry of the sample. IE is used to gain *qualitative* information from a sample (even complex shapes and geometries) by analyzing its resonant frequencies. This feature makes the technique well suited for applications in tolerance inspection and quality control for the manufacturing of complex parts. However, the technique also excels for quantitative measurements. For simplified geometries, including bars and discs, highly accurate quantitative elastic information may be collected if the other physical parameters (mass, geometry, and resonant frequencies) are measured. ASTM C1259-15 excellently outlines the procedure and methodology for quantitative measurements.[12] Specifically, the standard covers the methodology for determining the dynamic elastic properties for specimens of bar, rod, and disc geometries.

When using IE, various vibrational modes may be excited. To help isolate the excitation of certain modes, the sample is supported along vibrational "nodes" that undergo zero displacement during vibration. The point of impact is precisely controlled and positioned to isolate excitation of these modes. The ASTM standard calls for the excitation of two modes to calculate the dynamic Young's modulus,

dynamic shear modulus, and Poisson's ratio. The method and calculations are slightly different depending on the geometry. For rectangular bar specimens, the Young's modulus and shear modulus are determined from the flexural and torsional resonant modes, respectively. For disc geometries, the first and second natural vibrations of the disc are used to calculate Young's modulus and Poisson's ratio. After an initial impulse, the transient vibration is measured using a transducer that converts the physical movement into a voltage signal as a function of time. The frequency content of this signal is determined by transformation from the time domain to the frequency domain using a fast Fourier transform (FFT). The resonant frequency is identified from the frequency spectrum. The resonance is the lowest fundamental frequency of the particular vibrational mode and will have the largest amplitude in the frequency spectrum when the measurement is correctly performed.

Sample geometry is likely a matter of convenience. At the DEVCOM Army Research Laboratory, for instance, many research-grade ceramic specimens are fabricated using ceramic powders pressed in cylindrical dies that produce thin, cylindrical disc-shaped green bodies that are then sintered. Therefore, the current IE technique at ARL is set up for these disc-shaped samples, as shown in the schematic diagram for room-temperature measurements in Fig. 4. One main advantage is that measurements of these samples require little-to-no sample preparation, such as machining or polishing, which makes IE an extremely quick and convenient choice. Once the resonant frequency has been measured and identified using the previously described procedure, the Young's modulus, shear modulus, and Poisson's ratio may be calculated using equations and tables presented in the ASTM standard. Since the ARL setup is used for disc-shaped geometries, the following outlines the basic equations for determining the elastic properties of those types of samples (bar and rod geometries require different calculations).

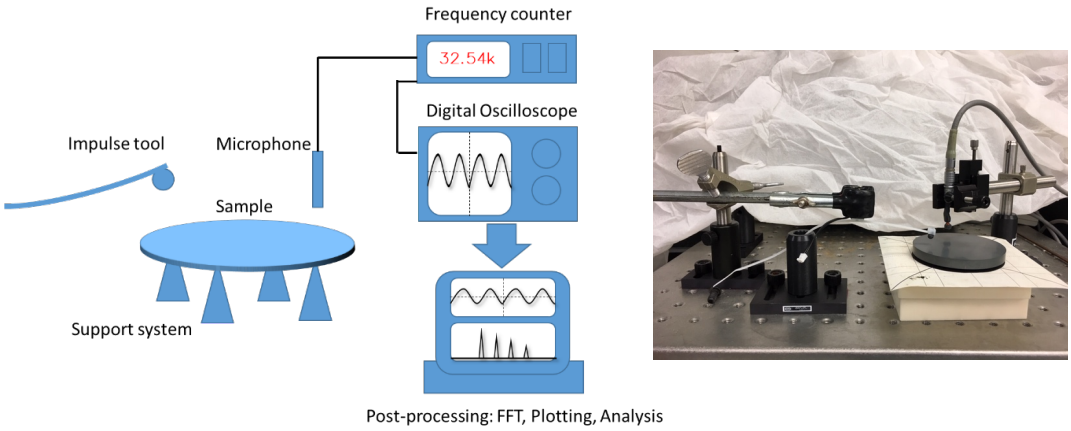

Fig. 4 Schematic of IE technique currently used at ARL for room-temperature measurements and photo of the position fixtures for the impulse tool and microphone

The resonant frequency is related to the physical properties of the sample by the following relationships[12]:

$$f_i = \frac{K_i}{2\pi r^2}\sqrt{\frac{A}{\rho t}} \tag{8}$$

where f_i is the natural resonant frequency, K_i is the geometric factor for the particular resonant frequency, r is the radius of disc, ρ is the mass density, t is the disc thickness, and the parameter A is the plate constant. The elastic properties are related through the plate constant as follows:

$$A = \frac{E_i t^3}{12(1-\mu^2)} \tag{9}$$

where E_i is the Young's modulus and μ is the Poisson's ratio of the material. The frequencies, f_i, where i = 1 or 2 for the first and second natural vibration, are measured from the impulse to the specimen. The equations may be rewritten to calculate a Young's modulus from each independently measured resonant frequency[12]:

$$E_i = [12\pi f_i D^2 m(1-\mu^2)]/(K_i^2 t^3) \tag{10}$$

where D is the diameter of the disc and m is the mass of the disc. The accepted value of Young's modulus is then determined by averaging the two calculated values using the equation:

$$E = \frac{E_1+E_2}{2} \tag{11}$$

To calculate E, both Poisson's ratio and the geometric constants, K_i, must first be determined. The Poisson's ratio is calculated using a polynomial equation that includes the ratio of the two frequencies ($f2/f1$), the ratio of the sample geometry (t/r), and a table of polynomial coefficients that depend upon the particular ($f2/f1$) ratio. Furthermore, the dynamic shear modulus, G, may be calculated using the well-known relationship $G = E/[2(1+\mu)]$. In summary, five measurements are required to calculate the Young's modulus and Poisson's ratio of a disc-shaped specimen using the ASTM standard: the radius, the thickness, the mass, and the two resonance frequencies.

An example of the FFT spectrum collected from a commercial silicon carbon (SiC-N) disc is shown in Fig. 5. The fundamental resonant frequencies, labeled f, of each mode (F1 and F2) are clearly visible and have the largest amplitude; that is, the largest frequency content of the collected signal. Odd harmonics of the fundamental ($3f$, $5f$, $7f$ …) are clearly visible with sequentially decreasing amplitudes. We find that well-behaved measurements on the disc geometries typically produce these odd harmonics in tandem with the fundamental. The Young's modulus and Poisson's ratio are calculated using the ASTM standard as E = 457.5 GPa and nu = 0.175. These values are close to published values of SiC-N of E = 460 GPa and nu = 0.14, albeit the measured Poisson's ratio is slightly higher.[13]

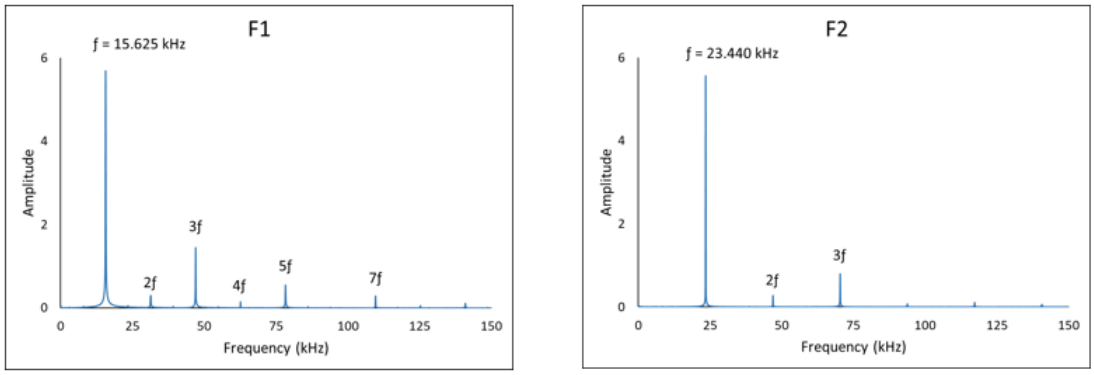

Fig. 5 FFT spectrum collected using IE on a commercial SiC-N disc

5. Comparison of Dynamic Methods

UPA, RUS, and IE are all dynamic methods capable of determining elastic property measurements, but each technique has its distinct advantages and disadvantages, as compared in Table 2. Previous studies[1] demonstrated the effectiveness of RUS and IE for providing superior precision and repeatability (when compared to static methods such as four-point bending and nano-indentation). In contrast to the RUS and IE resonance techniques, which utilize the frequency domain, UPA is a pulse

technique that uses the time domain to detect reflected signals as a function of acoustic impedance mismatch at various interfaces. While both RUS and IE institute frequency measurements, IE uses a single impulse, whereas RUS uses a drive transducer to excite a continuously varying input frequency into the sample.

Table 2 Comparison of dynamic testing methods

Method	Domain	Geometry	Sample type	Sample region	Sample size	Inspection speed	Dimensions required	Known data required
UPA	Time	Advanced	All	Local	Centimeters	Limited (manual)	Thickness	Density
RUS	Frequency	Simple	High modulus	Global	Millimeters	Rapid	All	Density, elastic
IE	Frequency	Simple	High modulus	Global	Centimeters	Rapid	All	Density

6. Conclusion

Each of the three dynamic techniques holds different advantages depending on the desired application. RUS and IE are typically associated with more simple geometries, such as bars, rods, and discs, and the equations for calculating various elastic properties change depending on the shape of the sample. In comparison, UPA is more flexible in terms of the shape of components that can be inspected. If the top and bottom surface longitudinal and shear signals can be identified during UPA, the necessary TOF values can be measured and elastic properties calculated, in spite of minor curvature or shape complexity, as they are carried out at the point of inspection.

While studies have shown that differences in elastic constant determination are not statistically significant when comparing resonance techniques such as RUS and IE, it has been pointed out that RUS requires an experienced operator, initial knowledge of approximate values ahead of time, and more time for analysis of results.[1] However, if these challenges are overcome, RUS holds advantages in evaluating smaller samples on the order of 1 mm, whereas IE is limited to centimeters.[1] RUS can be implemented in situ to high-temperature, pressure, and other extreme environments with minimal components, while mechanical strains can be applied and measured via lasers or electromagnetic fields. RUS is also advantageous in serving as the quickest and most effective method for pinging components with simple geometries, homogeneity, and narrow ranges of material properties as they result in strong, discrete resonances. It is capable of capturing a snapshot of the entire component, but not at identifying and locating specific problem regions. However, given the potential for error in accurately quantifying elastic properties when unaccounted-for changes in nominal dimensions and density are present, RUS may be best suited for qualification in the manufacturing environment, providing rapid go/no-go inspection. Process Compensated

Resonance Testing is an example of a hybridized form of RUS the uses formulated algorithms and trained data sets of “good” and “bad” components to automate inspection of like components, such as ceramic tiles. This type of method is where RUS-based techniques have demonstrated an advantage over UPA.

That being considered, UPA can be applied in ways that RUS and IE cannot, including inspection of different regions within the same component for comparison and contrast, defect detection at specific locations, and identification of features as a function of depth. UPA accomplishes this in pulse–echo mode, as the reflected signal from a feature with a mismatch in acoustic impedance can be detected and compared to top and bottom surface reflections to determine the location within the bulk of the sample. When seeking elastic property measurements, all of these factors should be taken into consideration to choose the best possible dynamic method for a given application.

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List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
Al_2O_3	alumina
ARL	Army Research Laboratory
A-scan	amplitude-scan
B_4C	boron carbide
DEVCOM	US Army Combat Capabilities Development Command
FEA	finite-element analysis
FFT	fast Fourier transform
IE	impulse excitation
NDE	nondestructive evaluation
PC	personal computer
RUS	resonant ultrasound spectroscopy
SiC	silicon carbide
SiC-N	commercial silicon carbon
TiB_2	titanium diboride
TOF	time-of-flight
UPA	ultrasound point analysis
WC	tungsten carbide

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FCDD RLW M
B CHEESEMAN
E CHIN
K CHO
W ROY
FCDD RLW MA
J SANDS
E WETZEL
FCDD RLW MB
C FOUNTZOULAS
G GAZONAS
J LIGDA
B LOVE
D MAGAGNOSC
J PITTARI
B POWERS
J SIETINS
Z WILSON
FCDD RLW MC
S WALCK
FCDD RLW MD
J LA SCALA
S WALSH
FCDD RLW ME
K BEHLER
V BLAIR
R BRENNAN
S COLEMAN
A DIGIOVANNI
J DUNN
M GOLT
M GUZIEWSKI
S HIRSCH
C HUBBARD
M IVILL
S KILCZEWSKI
M KORNECKI
N KU
J LASALVIA
T PARKER
P PATEL
S RAJU
A ROSENBERGER
W SHOULDERS
S SILTON
J SWAB
FCDD RLW MF
P GOINS
C HAINES
E HERNANDEZ
E HORWATH
FCDD RLW MG
J LENHART
R MROZEK
E NAPADENSKY
FCDD RLW PB
J MCDONALD
S SATAPATHY
T WEERASOORIYA
FCDD RLW PC
J CAZAMIAS
D CASEM
J CLAYTON
R LEAVY
J LLOYD
C MEREDITH
T SCHARF
C WILLIAMS
FCDD RLW PD
R DONEY
K STOFFEL
FCDD RLW LH
P JANNOTTI
L MAGNESS
D MALICK
FCDD RLW PE
C KRAUTHAUSER
P SWOBODA
FCDD RLW S
J CIEZAK-JENKINS
A WEST

5 DEVCOM SC
(PDF) FCDD SCP
J KIREJCZYK
FCDD SCP WI
R DILALLA
A FOURNIER
C LEWIS
FCDD SCP WP
D PHELPS

1 SFAE SDR SPIE
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