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Selecting a Nondestructive Testing Method, Part V: Ultrasonic Testing

This edition of TechSolutions *is the fifth installment in a series dedicated to the subject of nondestructive testing. The previous installments introduced the concept of nondestructive testing and focused on visual inspection, eddy current testing, and radiographic testing. The current article continues the series and provides a general and informative overview of the ultrasonic nondestructive testing method. In addition, this article will highlight some of the physical principles, inspection requirements, and implementation considerations involved in an effective ultrasonic inspection process. Once the series on nondestructive testing methods is complete, we will combine all of the articles into a valuable desk reference on nondestructive testing and place it on our website.* – Editor

INTRODUCTION

Ultrasonic testing (UT) is another widely applied inspection technology. Ultrasonic methods are an extremely diverse set of techniques based upon the generation and detection of mechanical vibrations or waves in test objects. The objects that can be tested are not limited to metals or even to solids.

The methods enabled by ultrasonic technology are often used to detect and size internal flaws in metals, ceramics and composites, but they can also be used to assess the integrity of interfacial material bonding, to measure thickness and extent of corrosion, and to determine physical properties such as the structure, grain size, and elastic constants of various materials.

The term ultrasonic refers to sound waves of frequency above the limit of human hearing, approximately 20 kHz. The frequencies between 1 and 10 MHz encompass the range used for most ultrasonic techniques, although lower and higher frequencies are sometimes used for special applications. Ultrasonic velocity in a material is a simple function of its modulus and density, and thus ultrasonic methods are uniquely suited to materials characterization studies. In addition, the sound waves are strongly reflected at physical boundaries where materials properties change, and thus they are often used for thickness measurements and crack detection.

HISTORY AND RECENT ADVANCEMENTS

The study of ultrasonics originated in the nineteenth century; however the use of ultrasonic waves for nondestructive testing (NDT) is more recent, beginning in the late 1920s. Developments since the 1930s enabled ultrasonic techniques to become a widely used NDT method. In the years following 1955, advancements in ultrasonics were rapid and extensive. The rapid development of instrumentation for ultrasonics, which was spurred by the technological advances from the 1950s, continues today. From the 1980s through the present, computers have provided technicians with smaller and more rugged instrumentation that have greater capabilities.

In recent years, ultrasonic imaging techniques have greatly progressed, and the need to extract exact data from UT has led to the development of more quantitative test techniques.[1] Other recent advancements, including development of non-contact techniques for the generation and detection of ultrasonic energy are evolving around lasers and eletromagnetic tranducers.[2] Phased array ultrasonics is now available in portable instruments. With this approach, the timed or phased firing of arrays of ultrasonic elements in a single transducer allows for precise tailoring of the resulting ultrasonic waves in the test object.[3, 4]

PHYSICAL PRINCIPLES

Ultrasonic inspection is based on introducing beams of ultrasonic energy (usually 0.1 to 25 MHz high frequency sound waves) into materials and determining the resulting perturbations in the energy in order to detect surface and subsurface flaws in the material. The sound waves travel through the material with some loss in energy (attenuation) and are also reflected at interfaces. The reflected beam, or in some cases the transmitted beam, is then analyzed to determine the presence, size and location of flaws and discontinuities.

The basic electronic instrument used in pulsed UT contains a source of voltage spikes to activate a piezoelectric transducer (the pulser) and a display mechanism that permits interpretation of the received ultrasonic acoustic impulses. Figure 1 shows a typical block diagram of the basic instrumentation system.

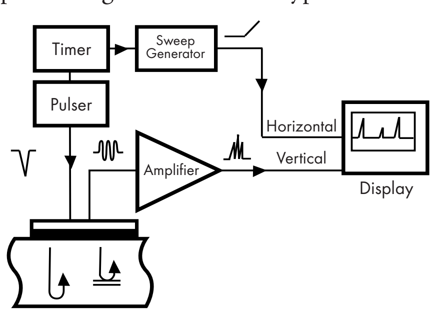

Figure 1. Basic Pulse Echo System for Ultrasonic Testing. [5]

In contrast to light waves or x-rays which are a form of electromagnetic energy, ultrasonic waves are a form of mechanical energy that consist of oscillations or vibrations of the atoms or molecules of a material. Ultrasonic sound waves behave much in the same way as audible sound: they propagate through solids, liquids and gases but not through vacuum. The interaction of ultrasonic waves with materials and flaws can now be successfully modeled using various simulation techniques.[6]

Wave Generation and Detection

In most cases, ultrasonic waves for NDT are generated and detected using piezoelectric transducers that require a couplant to transfer the ultrasonic waves between the transducer and the sample. Piezoelectric transducers contain piezoelectric crystals (e.g., barium titinate, lead zirconate, lead titinate) that change shape rapidly when an electric current is applied. They also behave in the reverse by generating an electric field when they are rapidly stressed and strained. Ultrasonic waves for NDT can also be generated and detected by several other methods. One such method utilizes non-contact air-coupled transducers, which are based on microelectromechnical systems (MEMS) technology. Another method generates a non-contact pulsed laser by rapid thermal expansion or ablation at the surface of the sample, the detection of the generated ultrasonic waves is accomplished using laser interferometery or air-coupled transducers. In addition, magnetic metals can also be inspected by ultrasonics using noncontacting electromechanical acoustic transducers (EMATS) to both generate and detect the ultrasonic waves.[5] Ultrasonic inspection usually detects flaws or discontinuities by one or more of the following:

- Reflection of sound from interfaces that are materials boundaries or discontinuities in the material
- Transit time or time of flight of the ultrasonic waves
- Attenuation of the ultrasonic waves
- Features in the spectral response of the transmitted or reflected signal

Types of Ultrasonic Waves

There are a number of different types of ultrasonic waves, including: longitudinal waves, transverse or shear waves, surface or Raleigh waves, and Lamb or plate waves. Longitudinal waves travel through the material with each particle vibrating parallel to the direction of the wave motion as an alternating series of compressions and rarefactions; they are the most commonly used type of waves for ultrasonic inspections. Transverse waves are also used extensively in ultrasonic inspections and are analogous to the vibrations of a rope that is shaken rhythmically. The atoms or molecules vibrate up and down in a plane perpendicular to the direction of wave propagation. Surface waves, sometimes used for ultrasonic inspection, travel along the flat or curved surface of relatively thick parts. Lamb waves, used in some cases for ultrasonic inspection, propagate in plates of material that are a few wavelengths thick. Reflections at interfaces depend to a large degree on the physical state of the materials at the interface and to a lesser degree on the specific physical properties of the materials. Tables 1 and 2 show the main advantages and disadvantages of ultrasonic testing.

INSPECTION REQUIREMENTS

Ultrasonic methods of inspection are applied to measure a variety of material characteristics and conditions. They are applied in the flaw detection mode for the detection of surface and internal anomalies in test objects. Test objects must

Table 1. **Advantages of Ultrasonic Inspection. [5]**

• Superior penetrating power, up to a few meters in many parts and up to 6 meters axially
• High sensitivity, permitting the detection of extremely small flaws
• Greater accuracy in determining the position of internal flaws, estimating their size, and characterizing their orientation, shape and nature
• Only one surface needs to be accessible
• Operation is electronic, which provides almost instantaneous indication of flaws. Suitable for immediate interpretation, automation, rapid scanning, in-line production monitoring, and process control
• Volumetric scanning ability to inspect from the front surface to the rear surface of a part
• Nonhazardous operation
• Portability
• Provides a digital output that can be used by a computer to characterize defects and materials properties

Table 2. **Disadvantages of Ultrasonic Inspection. [5]**

• Manual operation requires careful attention by experienced technicians
• Extensive technical knowledge is required for the proper development of inspection procedures
• Parts that are rough, irregular in shape, very small or not homogenous are difficult to inspect
• Discontinuities that are in a thin layer immediately below the surface are difficult to detect
• Couplants are usually required to provide transfer of ultrasonic wave energy between transducers and parts being inspected
• Physical reference standards are needed, both for calibrating equipment and characterizing flaws

support propagation of acoustic energy and have a geometric configuration that allows the introduction and detection of acoustic energy in the reflection, transmission or scattered energy configurations. General process steps include [7]:

1. An ultrasonic transducer is located in contact or in close proximity to the test object
2. The transducer is energized in a pulsed mode to direct and propagate acoustic energy into the test object
3. Acoustic energy is transmitted, reflected and scattered within the test object
4. Energy within the test object is transmitted or redirected by internal interfaces (test object geometry features or internal anomalies)
5. Transmitted or redirected energy from the test object is detected by a transducer located on or near the test object
6. The transmitted or redirected energy is analyzed in the time and/or frequency domains, and interpretation of the internal condition of the test object is made by the pattern and amplitude features.

Special equipment and specialized probes are required to perform the inspection. Procedure development, calibration artifacts and process control are required to assure reproducibility of response in the selected test object. The method is a surface and volume inspection process, and procedures are varied to increase sensitivity and resolution of specific test object features.

Manual and Automatic Techniques

Depending on the application, the inspection may be performed manually or automatically. Manual (hand) scanning is performed using instruments that have an oscilloscope type readout. Operator interpretation is made by pattern recognition, signal magnitude, timing and respective hand-scan position. There may be significant variations in instrument read-out due to variations in manual scanning. A permanent record of inspection is not provided by this method.

Automated scanning is performed using an instrumented scanner that keeps track of probe position and automated signal detection (time, phase and amplitude) such that a response map of the internal structure of the test object can be generated. Resolution of the system is somewhat dependent on the fidelity of the scan index and on the filtering and signal processing that are applied in signal detection. A scan map and/or commented report may be generated by automated

Table 3. **Manual (Hand) vs. Automated Scanning and Inspection. [7]**

	Manual	Automated
Cost of Inspection	Low	Moderate
Cost of Equipment	Moderate	High
Operator Skill Requirements	High	Moderate
Process Control Requirements	Moderate	High
Process Variance/Margin Requirements	Moderate	Low

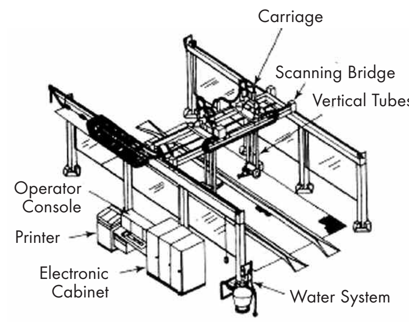

Figure 2. **Large Automated Quality Control System Containing Modular Ultrasonic Test Component.[5] (Copyright 2007 © Reprinted with permission from the American Society for Nondestructive Testing.)**

ultrasonic scanning and instrumentation systems. The relative features of manual scan and automatic scan are summarized and compared in Table 3.

PRACTICAL CONSIDERATIONS

Equipment Portability

Ultrasonic testing instruments may be grouped into three categories. The first category includes manual instruments that are typically portable send/receive units (there are many commercially available to choose from). The second category includes customized instruments that are programmed for specific industrial applications and are usually not portable (some of these contain large water baths or “water squirting systems” and automated scanning devices). Figure 2 shows a typical large, automated ultrasonic quality control system. Finally, the third category includes special purpose systems that are used typically in the laboratory. Within the past few years, a new, small, portable, hand-held ultrasound camera has become available that provides a direct image of the part being inspected.[8]

Training/Certification

One of the most critical aspects of the UT process is the qualification of the testing personnel, because the quality of the test is highly dependent on the skills and knowledge of the inspector. Even with highly automated equipment, correct procedures including calibration must be carefully followed to achieve acceptable results. There are a number of commercially available ultrasonic NDT training courses available. In addition, the American Society for Nondestructive Testing (ASNT) has three programs for the qualification and certification of NDT personnel [9]:

1) *ASNT Recommended Practice No. SNT-TC-1A* provides guidelines to employers for personnel qualification and certification in NDT, and it requires the employer to develop and implement a written practice for personnel qualification and certification in NDT.

2) ANSI/ASNT CP-189, *Standard for the Qualification and Certification of Nondestructive Testing Personnel*, resembles SNT-TC-1A but establishes specific requirements for the qualification and certification for three different levels of ASNT certification. Level I and Level II are specifically covered, while Level III references an examination administered by ASNT. It should be noted that CP-189 is a national

consensus standard as defined by the American National Standards Institute (ANSI).

3) The ASNT *Central Certification Program (ACCP)*, unlike SNT-TC-1A and CP-189, is a third party certification process that identifies qualification and certification attributes for Level II and Level III NDT personnel. The ASNT program certifies that the individual has the skills and knowledge for many NDT method applications.

In addition to ASNT programs, the Aerospace Industries Association has promulgated a national consensus standard for certification and qualification of NDT personnel in the aerospace industries: *NAS 410, National Aerospace Standard (NAS) Certification and Qualification of NDE Personnel*. In the international arena, the International Standards Organization (ISO) has established international standard ISO 9712, *Nondestructive Testing-Qualification and Certification of Personnel*, Third Edition. [10]

Cost

Hand-held, portable UT equipment is generally low cost (around $10,000) and is intended for discontinuity detection and thickness gauging. These instruments provide a video display of the ultrasonic signals. More elaborate, conventional transportable UT systems generally cost between $25K and $30K. Industrial production ultrasonic inspection systems are often modular and offer multi-channel capabilities. These systems can be easily optimized for a particular production requirement through plug-in modules and changes in computer control software. The initial cost of a modular system is typically around $50,000. Other hardware, such as water immersion tanks, water squirting systems, laser sound generation, and automated scanning systems, can also substantially add to the cost of the systems (another $50,000 or more).

SELECTED EXAMPLES

Figure 3 shows an inspector examining a composite material that sustained impact damage. The immersion tank is used for large structures but can be used for small components as well (Figure 4). The ultrasonic scanning system capable of high resolution enables precision inspection of a vast array of specimens while maintaining exacting precision in the inspection area of interest. Figure 5 shows an aircraft being inspected with a portable UT system. A permanent ultrasonic testing station, as shown in Figure 6, can provide continued high quality testing capabilities for various materials and components.

Figure 3. **An Impact-Damaged Graphite/Epoxy Specimen is Positioned for Inspection in the Immersion Tank for Large Structures.**

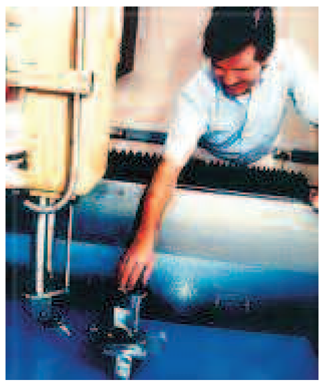

Figure 4. **A Prototype Composite Airfoil is Aligned for Ultrasonic Inspection. Automated inspections can be made of small or large components in this tank.**

Figure 5. **Manual Ultrasonic Inspection of an Aircraft.**

Figure 6. **A Materials Engineer Positions the Ultrasonic Transducer for a Scan while a Computer Specialist Enhances Scanning and Image Analysis Capabilities.**

CONCLUSIONS

Ultrasonic testing is a mature technology with a strong physics foundation and maturing modeling of inspection results capability. There is widespread availability of user-friendly, affordable, commercial equipment and complete turnkey systems. Ultrasonic testing equipment providers offer a broad array of equipment types to meet the needs of users, including: hand-held devices; portable, computerized multifunction instruments; modular systems for industrial production; and laboratory instruments for R&D. The following ultrasound sources and detectors can be chosen to meet inspection requirements: piezoelectric transducers; EMATS; lasers and laser interferometers; and air-coupled transducers.

Ultrasonic NDT is widely used in manufacturing quality control, manufacturing acceptance testing, and for in-service inspection. It can be readily applied to metals, composite laminates, ceramics, and polymers to locate and define discontinuities. It is used to determine thickness of materials, the quality of adhesively bonded structures, the mechanical modulus of materials, and materials characteristics such as grain size and orientation. Many applications are found in the petroleum and aerospace/aeronautical industries, and the method is commonly used in nuclear power plants and on structural concrete infrastructure.

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Ultrasonic Testing Summary

Discontinuity types (e.g., what types the method can detect)	• Cracks • Holes • Corrosion • Impact damage • Delaminations
Size of discontinuities	• Capable of detecting embedded flaws with a surface area of 1.3 mm^2 or 0.002 in^2
Limitations	• Complex geometries and very small components are difficult to inspect • Detailed inspection procedure
Advantages	• Superior penetrating power in all media (solid, liquid, gas) • High sensitivity • Locates flaw/discontinuity location accurately • Only one surface must be accessible to carry out inspection of component/system • Can be used to determine physical properties of materials (e.g., structure, grain size, elastic constants, etc.) • Can be used on metals, ceramics, polymers, composites and laminates
Inspector training (level and/or availability)	• Training available through ASNT, ASNI, etc.
Inspector certification required	• Strongly recommended that inspection personnel are trained and certified
Equipment	• Portable equipment available • Automated systems capable of inspecting large components available
Relative cost of inspection	• Relatively inexpensive equipment costs ($10K - $50K), but larger systems and more sophisticated equipment are more costly

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